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STREET TRAFFIC SIGNALS, WITH PARTICULAR REFERENCE TO VEHICLE ACTUATION

By F. G. TYACK, Associate Member.

SUMMARY

The author describes current practice in street traffic signalling, dealing particularly with vehicle-actuated signals as adapted for use in Great Britain. Detailed descriptions are confined to the system with which the author is most familiar (the Autoflex vehicle-actuated system). Brief references are, however, made to other systems and to practice in other parts of the world. All parts of the equipment are treated, including signals, controllers, and detectors. The paper is divided into two main portions, the first dealing with generalities and isolated intersections and the second with interlinking of numbers of intersections. The subject is treated from the traffic aspect as well as from the electrical aspect, and details of the performance of certain of the schemes are given.

HISTORICAL SURVEY

It will probably surprise many people to learn that a traffic signal was in use in London as long ago as 1868; as far as can be ascertained this was the first instance of the use of a mechanical device for street traffic control. This early signal comprised a semaphore arm, with red and green gas lamps for night use, and was erected in Westminster. It would seem that present-day traffic problems are not altogether the result of the development of mechanical transport, for even at that time the desirability of some auxiliary signalling means was realized. Unfortunately for the development of traffic-control methods in general, an explosion put an early end to the experiment.

Semaphore arms and other mechanical signals are still in use in some parts of the world, though they are rapidly giving place to the more familiar lamp type. Semaphore signals are still to be found in use on Tower Bridge in London, and it is only recently that they have disappeared from general use in Brighton.

Early in the present century, colour-light signals were introduced on single-line tramways, notably at Pontypridd and Swindon, and, later, more powerful lamps of the same type were introduced on railways.

Modern colour-light signals were first used for street traffic control in New York about 1918, and the fact that they were not used in Great Britain until considerably later may be attributed partly to the setback resulting from the War and partly to the excellence of the police control in this country. Conditions became increasingly difficult, however, with the post-war growth of motor traffic, and about 1925 an attempt was made to co-ordinate the actions of the police in Piccadilly, London, by means of a series of railway colour-light signals. These signals were retained in use for a short period only.

In 1926 the first modern British traffic signal was installed at a busy road junction in Wolverhampton. This signal was suspended above the intersection, and the only reason why it was not retained in use was that at that time there was no legislation to enforce obedience to its indications.

The early road signals were all manually operated, and it was perhaps a natural step to the mechanically-controlled fixed-time signal. This type consists of a mechanism arranged to measure off arbitrarily-determined "go" and "stop" periods. Fixed-time signals were found to be a cheap solution of the problem of accident prevention, but they were inefficient as far as traffic-carrying qualities were concerned, particularly at places with variable traffic, as their indications had no relation to the actual traffic conditions. For obvious reasons the unnecessary delays occasioned did not help to establish confidence in automatic signals.

Attempts to render fixed-time signals more efficient for the major traffic-changes, such as from rush hours to slack hours, were made when "programme" controllers were introduced. These controllers, so to speak, changed their tune from hour to hour in accordance with a predetermined programme chart, which was operated on the principle of the player-piano. Although this was a definite advance, the signals still had no regard for the actual traffic conditions.

Streets having a large number of crossroads were signalled by means of fixed-time signals which were so timed that the traffic flow was facilitated. The most common method of such co-ordinated control was the "flexible progressive" system, the principle of which was that the vehicles, having once entered the system, should be able to "progress" completely through it without further hold-ups, provided that they moved at the predetermined progressive speed. This arrangement, however, was also subject to the general defects of all fixed-time systems.

The ideal system must not hold up traffic unnecessarily, and should stop traffic movements only when such movements are definitely obstructive or dangerous. In other words, the ideal system should be endowed with the discriminating and signalling powers of the traffic policeman, but with as few of his limitations as possible. The logical solution of this problem is that the signals should be operated by the vehicles themselves. This was done in the early tramway signals already mentioned, but at that time there was no attempt to apply the principle to vehicles other than tramcars.

The first attempts at vehicular control of ordinary traffic signals took place in the U.S.A., where microphones were arranged at the sides of the roads and notices were erected requesting drivers to sound their horns. The

microphones had obvious disadvantages, and later gave place to electrical contacts in the paths of the intersecting traffic streams. Vehicle-actuated signals were introduced into this country in 1932, and have since been very widely installed. As their capabilities have become better understood and the system has developed, so more and more difficult crossings have been signalled, and some of the most recent developments lie in this direction. Perhaps the most important developments have been the large interconnected systems of vehicle-actuated signals which have been installed in London and in Glasgow, and which were brought into use during 1935.

SIGNAL INDICATIONS

The 3-aspect colour-light signal is most generally employed. The indications vary, particularly with regard to the amber period (the period when right-of-way is being transferred), but in Great Britain matters have been very much simplified by the action of the Ministry of Transport in laying down a definite order, as follows:—

Red:	Stop at the " stop " line.
Red with amber:	Be prepared to take right-of-way.
Green:	Proceed with caution.
Amber:	Stop, if the " stop " line has not been crossed, unless it is dangerous to do so.
Green arrow:	You may proceed with caution in the direction indicated, but not elsewhere.

In South Africa the 3-aspect signal is also used, but there are at least three different sets of indications. In Durban the signals give the British indications, while in Johannesburg green is shown as well as amber when the right-of-way is being taken from a road, and in Cape Town amber is shown on one road while red alone is shown on the opposing road.

A method which has been used extensively in Paris is the single-aspect red signal, traffic being allowed to pass freely except when the lamp is illuminated. The theory that probably underlies this type of signal is that drivers should *always* be proceeding with great care and at such a speed that they can stop at very short notice. In such circumstances the green signal, which can be construed to indicate the necessity for abnormal caution, is considered redundant. (Recent installations in Paris have incorporated 3-aspect signals, not only post-mounted as in this country but also sunk in the surface of the roadway.)

Time-indicator signals exist in several forms, though not in Great Britain. The most usual form would appear to be the clock face with red and green sectors, in which a hand rotates across " go " and " stop " sectors, so giving drivers an indication of the amount of unexpired right-of-way time. Time-indicator signals have perhaps been subject to more attention from private inventors than any other type, but as they are limited to fixed-time operation they have no place among modern signalling equipment.

One other modern type of signal deserving attention is the portable type used during road works in and around

London. This is a semi-mechanical type giving both semaphore and colour-light indications. Power is supplied from batteries, and the signals are hand-controlled by means of push-buttons located at a central point.

SIGNAL CONSTRUCTION AND SITING

The earliest colour-light signals were constructed specially for the intersections at which they were to be used, and were generally suspended over the centres of the intersections. From time to time one hears suggestions that signals should again be centrally suspended, and it may therefore prove advantageous to put on record the disadvantages of the method, as follows: (*a*) Drivers' attention directed up into the air instead of to the pavement edge and on eye level, where obstructions are likely to be encountered. (*b*) High initial cost. (*c*) High cost of maintenance. (*d*) Drivers in saloon cars unable to see the signals at close range.

The British standard arrangement of signals (shown in
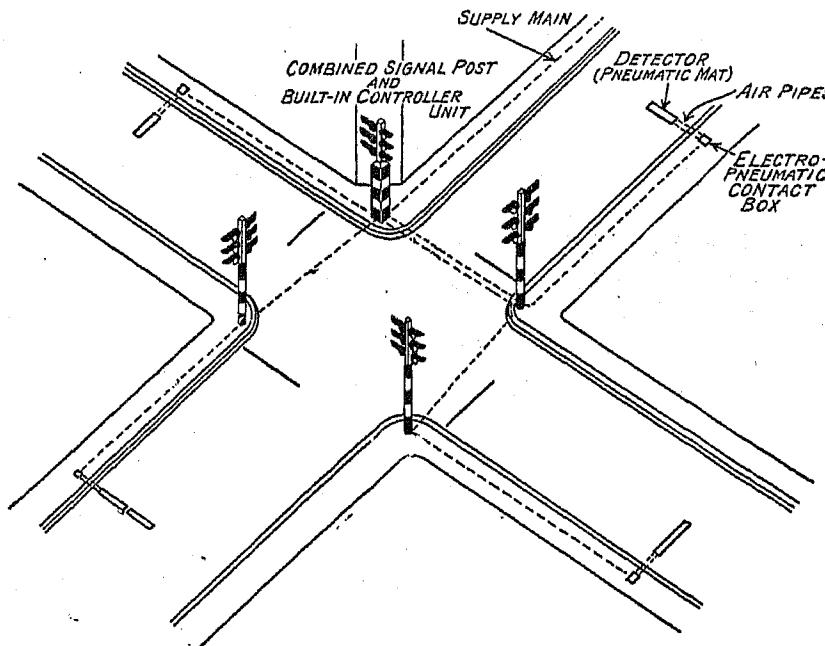
Fig. 1.—Equipment of a typical intersection.

Fig. 1) is that a " primary " signal is always placed on the near side, just beyond the " stop " line, and a " secondary " signal several yards farther on and either directly in front of the traffic stream or to the right of it. Other signals are placed elsewhere as required. The standard height of the lowest lamp is 7 ft. 6 in., this being sufficient to prevent concealment of the signals by pedestrians. The standard height is increased where there are unusual obstructions. The lamp-houses on traffic aspects are arranged in the order red, amber, green from top to bottom, as the red signal, being the most important, is thereby least liable to accidental obstruction. The red signal lens has inscribed on it the word " stop," but the amber and green lenses bear no wording except in some of the earlier installations. The colours of the lenses are very closely defined. A 60-watt vacuum lamp with a screw cap and with a closely-defined light centre is generally used. The standard lens has a diameter of 8 in. The signal posts and lamp-houses are rendered conspicuous by the painting-on of alternate black and white bands, each 12 in. in height.

The construction of the lamp-houses varies according to

the manufacturer, as also does the angle at which the lamp is operated. One common type, shown in Fig. 2, comprises a "top-of-post" assembly carrying 3, 6, or 9 hemispherical lamp-houses (for 1-way, 2-way, and 3-way signals respectively) attached by means of ball-and-socket joints which permit adjustment in all directions through a solid angle of approximately 15°. It should


15° ADJUSTMENT IN ALL DIRECTIONS FOR ALL ASPECTS
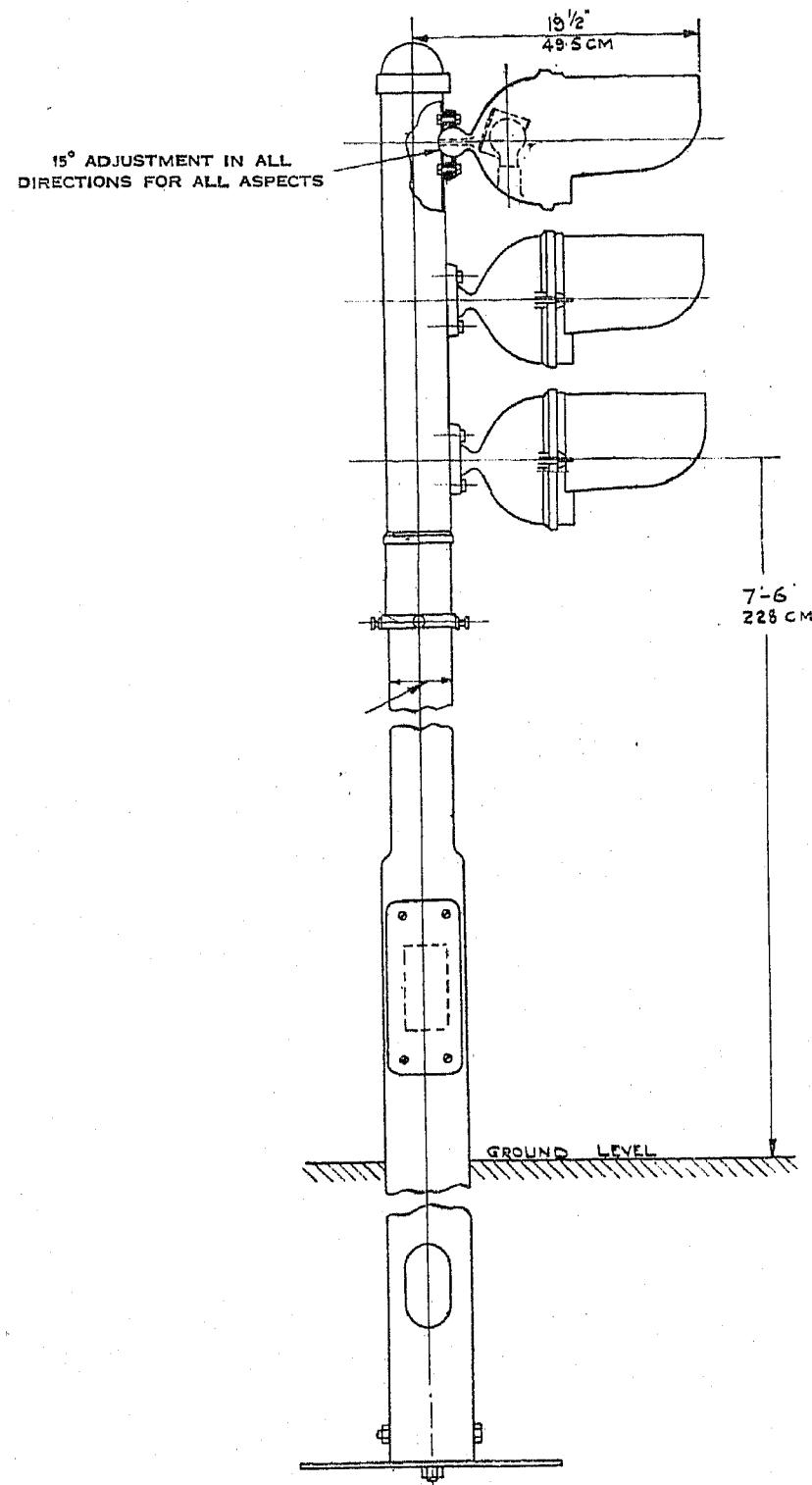
Fig. 2.—One-way adjustable-face traffic signal.

be noted that adjustment is not limited to 15°, as the assembly can also be rotated. The assembly is square in plan, and one side is detachable to give access to the terminals and cabling in the interior. In this type considerable attention has been given to the avoidance of "phantom" (the illuminated appearance of an unlighted signal due to reflection of light from the sun, motor-car headlights, etc.), and very satisfactory results have been achieved by the use of refracting lenses instead of para-

bolic mirrors. The early examples of this type embodied lenses divided horizontally in such a manner that the upper portion threw forward a concentrated beam of approximately 700 candles, visible from a great distance but through a solid angle of approximately 5° only (comparable with the beams emitted by railway signals), while the lower half radiated light varying in intensity approximately from 100 to 200 candles but visible from an angle of 40°. These lenses, however, did not prove generally popular; they have been replaced for new work by a uniformly refracting lens which does not give the long-distance beam.

It is necessary for the signals to be shielded efficiently so that there is no possibility of misinterpretation by drivers (including railway drivers) for whom the indications are not intended, and this is achieved by the use of the most appropriate of a large range of visors. When the effect of the sun shining on to the lenses is particularly troublesome a special louvre is fitted. This embodies slats which permit vision of the signals from below the horizontal but which effectively prevent light from reaching the lenses from above the horizontal.

Green-arrow lamp-houses are fitted to the left or the right of red signals when required. Green-arrow lenses are also fitted in place of normal green lenses when certain movements are prohibited (one-way streets).

PEDESTRIAN SIGNALS

Much attention has recently been devoted to the matter of signalling pedestrian traffic, and after considerable experimenting a standard scheme has been evolved. An obstacle in the past was that pedestrian signals could be misinterpreted by vehicle drivers, and it was consequently not possible to fit the ordinary type of signal except when well away from road intersections. When pedestrian periods were desirable at road intersections "overlapping red" periods were provided, but no special pedestrian indications were given. This obstacle was overcome by the use of signals bearing the words "Don't Cross" in red, and "Cross Now" in white. When no special pedestrian periods were provided it was, of course, impossible to use such indications owing to the dangers of turning traffic, and pedestrians were still expected to exercise great care. The present standard scheme is as follows:—

(a) The words "DON'T CROSS" are not used, as experience has shown that they are not observed and it is unreasonable to expect pedestrians to wait if there happens to be no vehicular traffic.

(b) At ordinary junctions without pedestrian periods additional signal faces consisting of the usual red, amber, and green signals are erected for the guidance of pedestrians, but these do not bear any instructions and the green light must not be regarded as guaranteeing safety.

(c) At ordinary junctions with pedestrian periods there are signals consisting of one lens only, bearing the words "CROSS NOW" in white and illuminated only during the pedestrian period.

(d) At pedestrian crossings away from road junctions the pedestrian signals consist of a plain red lens and a lens bearing the words "CROSS NOW" in white.

TRAMWAY SIGNALS

As already stated, colour light signals were in use on tramways some 20 years before their use for ordinary traffic. During that period their indications were ignored by drivers of vehicles other than trams, but it has now become necessary to substitute a different form of signal where special tramway indications are required. The signal adopted for this purpose is the " position light " signal, and comprises three white lamps arranged in the form of a triangle. The indications correspond to the indications of the upper quadrant signal used on railways, and are as follows:—

Two lamps illuminated in horizontal formation: STOP
Two lamps illuminated in sloping formation :   GO

Examples of position light signals may be found at the north end of the Kingsway tramway subway in London.

GROUPING OF ROADS FOR SIGNALLING PURPOSES

It is customary to group together the diametrically opposite members of a through road and to treat them as one for signalling purposes. Where, however, there is a preponderance of turning traffic this is not always practicable, and the roads are given individual, or partially individual, treatment. It is only very rarely justifiable to give right-of-way simultaneously to roads not opposite one another.

TRAFFIC CONTROL SCHEMES: GENERAL DESCRIPTIVE TERMS

There are numerous methods of operating traffic-controllers to suit varying road layouts and traffic conditions, and with the rapid increase in the number of signalling schemes for complex junctions, standardization of descriptive terminology has become essential.

Descriptions of controllers have up to the present generally included a number of " phases " or " cycle-parts," but the meanings of these expressions have been vague, and the terms have sometimes been regarded as synonymous. " Phase," in particular, has been far from clear, as it has sometimes been used to mean cycle-parts, sometimes the number of roads, and sometimes the number of groups of signals. In order to obtain a clear idea of the meanings of the above terms, reference to the analogous case of 3-phase alternating current is suggested, as shown in Fig. 3(a). It will be agreed that all phases of an alternating-current supply occur at all parts of the cycle. Representing the traffic flow at a straightforward crossroads in a similar manner on a horizontal time-base gives Fig. 3(b). There are two phases and two cycle-parts, and this scheme may be described as " 2-phase 2-part-cycle." For obvious reasons it would not be practicable to represent three or more phases on a diagram of this nature, and Fig. 3(c) serves the same purpose without this restriction. The phases are represented by the signal colours showing during the various parts of the cycle. Traffic-flow diagrams of the type shown in Fig. 3(d) may be associated with the various cycle-parts. Diagrams of the types shown in Figs. 3(c) and 3(d) are regularly produced and used when analysing
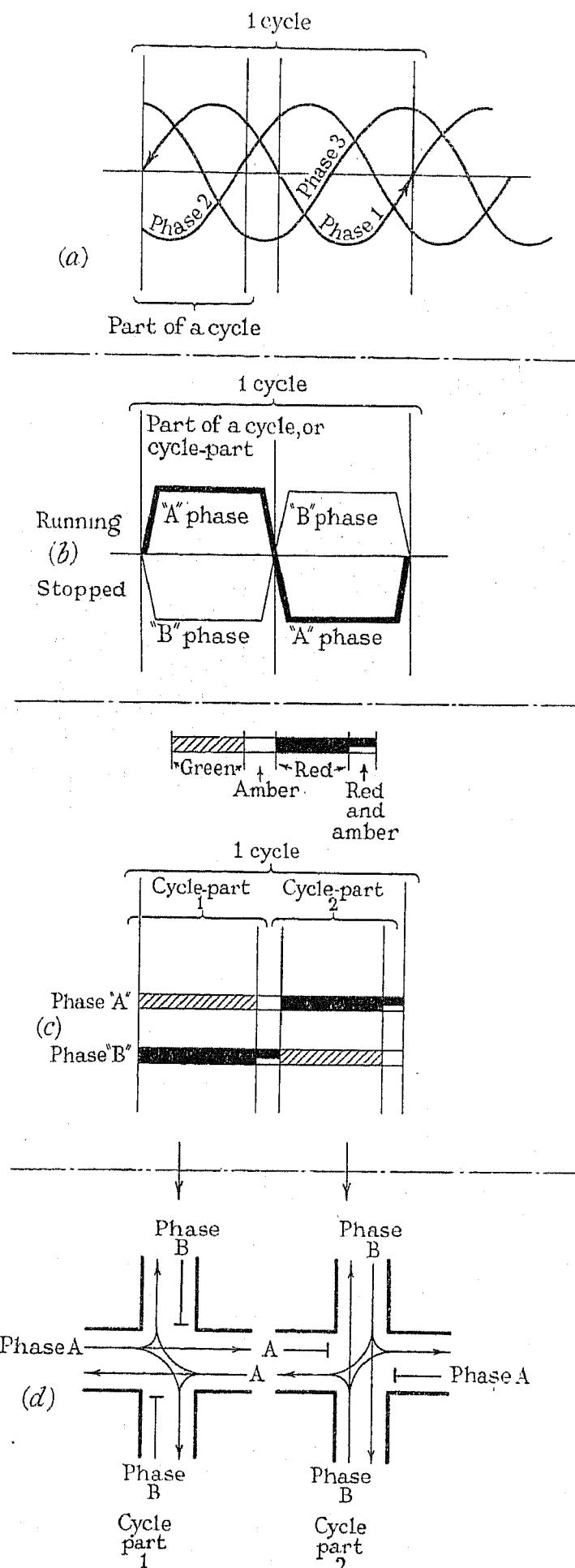

Fig. 3.—Derivation of traffic terms and diagrams.

(a) Parallel case of 3-phase alternating current. All phases occur during all parts of the cycle.

(b) Traffic diagram, constructed in same manner as the alternating-current diagram shown in (a), to represent 2-phase 2-part-cycle control scheme.

(c) Traffic diagram with phases represented conveniently as straight lines.

(d) Diagrams showing actual traffic flow during various parts of the cycle related directly to (c) as indicated by arrows.

customers' requirements. Fig. 18 gives representations of control schemes for complex junctions.

A study of these diagrams indicates the necessity for certain definitions, as follows:—

(1) *Cycle.*—One complete sequence of aspects (B.S.S. No. 505—1937, Definition 11).

(2) *Cycle-part.*—The duration from one signal-change to the next, excluding amber periods.

(3) *Traffic lane.*—A single file of traffic.

(4) *Traffic phase.*—A group of streets or traffic lanes which have running and stopped periods at the same time as one another.

(5) *Controller phase.*—A group of signals which have running and stopped indications at the same time as one another.

The numbers of traffic phases and controller phases are generally identical, but can differ if two or more groups of signals are arranged to control a single stream of traffic, as in Fig. 18(c).

When referring to " cycles " and " parts," the more important word should be placed last, the other word being regarded as adjectival. Thus, " 5-part-cycle " describes the cycle, and " cycle-part 2 " describes a particular part of the cycle. It is also convenient to *number* the cycle-parts, and to *letter* the phases.

BASIC PRINCIPLES OF VEHICLE ACTUATION

In order that the signals may be operated in accordance with the actual traffic requirements it is necessary for the traffic movements to be noted by suitable equipment, and for the controller to be so constructed as to respond to the information passed to it by the movement-noting equipment. The controller then instructs the drivers by means of the signals.

There are two main types of vehicle-actuated traffic control equipment, and while both achieve approximately the same results the methods of operation are widely divergent. In both systems " detectors " are installed in the paths of the approaching traffic streams, but in one system the detectors are operated electrically and in the other electro-pneumatically. One controller effects its switching by means of a rotating camshaft, while the other employs telephone-type relays. It will be possible to describe in detail only one of these systems.

The functions of the equipment may be summarized as follows:—

(a) Vehicles approaching the intersection along the road having right-of-way must normally be permitted to pass well into the intersection before the signals change.

(b) Vehicles approaching the intersection along a road not having right-of-way must normally be afforded right-of-way immediately if there is no conflicting traffic, or alternatively when the first suitable gap in the cross-traffic occurs.

(c) If no suitable gap in the cross-traffic occurs within a reasonable time of the registration of a demand, the traffic must be arbitrarily interrupted and the right-of-way transferred. Traffic which is arbitrarily interrupted in this manner must not be forgotten, and the right-of-way must be returned to the road from which it has been taken without further demand.

(d) On right-of-way being given to a road, the traffic waiting at the " stop " line must be afforded reasonable

time to start up and pass into the intersection before right-of-way is transferred elsewhere.

The detectors are generally installed approximately 100 ft. from the " stop " line, this distance being sufficient for braking from ordinary speeds in the event of the right-of-way being transferred just before the detector is struck (see Fig. 1).
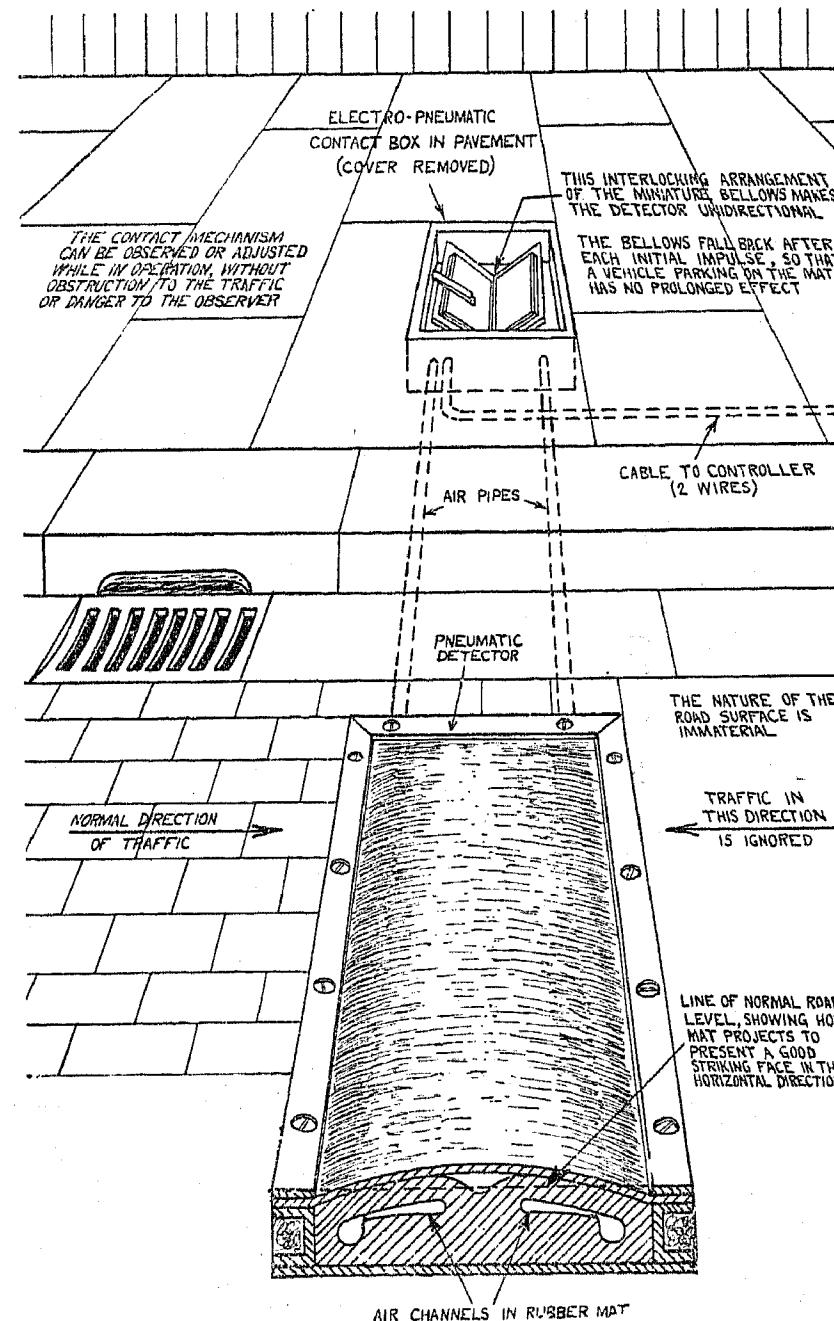

Fig. 4A.—Explanatory diagram of electro-pneumatic detector.

DETECTORS

The detectors form the equivalent of the eyes and ears of the traffic policeman, and as such must report as accurately as possible all the traffic movements which would be taken into account by a policeman. They must be robust and weatherproof, and must be fully sensitive to all the types of traffic for which they are intended. They must also, when required, ignore false traffic conditions such as vehicles leaving the intersection on the wrong side of the road, or parking in the vicinity.

The Electro-pneumatic Detector

The electro-pneumatic detector (Figs. 4A and 4B) is an example of the benefits which can be obtained by judicious

inter-working of air and electrical equipment. The only equipment in the road is a rubber mat through which pass two longitudinal air channels. There is no equipment which can be damaged by the traffic. A contact box is located under the pavement and is connected to the road mat by piping. The contacts can be inspected under actual service conditions without obstruction to the traffic or danger to the observer.

The top of the mat projects slightly above the road level to present a good striking face, so that it is not possible for vehicles to jump over without registering. As the channels in the mat are depressed, so miniature bellows in the contact box become inflated. There are two pairs of bellows, one associated with each channel, mounted at right angles to one another so that only one can be operated at a time. The bellows associated with that side of the mat which is normally depressed first is fitted with an electrical contact.

Vehicles approaching the intersection inflate the contacting bellows for periods proportional to the times of

Overhead Tramway Detectors

The skate generally employed comprises two metal strips arranged roughly in the form of an inverted V on top of the trolley wire but insulated therefrom, the trolley wheel completing the circuit from the wire to the skate.

The type used on tramways having bows in place of trolley poles, as in Glasgow, consists of a scoop-shaped member resting on top of the trolley wire and projecting below it, so that on the passage of a bow it is deflected upwards. By means of the hinging and a crank a plunger is operated and the circuit is completed.

The overhead tramway detectors are connected via protective equipment to special high-voltage relays fitted on the tramway standards, and these, by means of repeating contacts, pass the impulses to the controllers.

Conduit Tramway Detectors

Two types embodying levers operated by the ploughs have been developed, one with a direct electrical contact


Fig. 4B.—Cross-section of latest-type pneumatic detector.

occupancy of the mat and inversely proportional to the speeds. Impulses indicating the speeds of the vehicles are thus transmitted to the controller. Vehicles leaving the intersection and passing over the mat in the wrong direction inflate the " interlocking " bellows, which prevent operation of the " contacting " bellows so that no pulse is transmitted. All normal detectors of this type are thus unidirectional.

The bellows have a very small air capacity and are consequently sensitive to the lightest vehicles. In order to prevent damage by the large volumes of air displaced by heavy vehicles, and to permit self-adjustment to the varying atmospheric conditions, air leaks are provided in the system by means of felt washers. The air leaks also serve to restrict the inflated state of the bellows to the actual duration of the movement of air, and it follows that a vehicle parking on a mat is completely ignored after arrival, while subsequent traffic registers in the normal manner. This feature is particularly useful when detectors are installed opposite entrances of public buildings. The detectors are shaped on site to suit the camber of the road.

and the other with a piston and cylinder, the latter for use with pneumatic detectors. The latter is connected by means of a pipe to the normal contact box, and consequently affords all the features of pneumatic detection.

A magnetic type has also been developed recently comprising a permanent magnet on one side of the conduit slot, with an armature fitted on the other side of the slot. The armature carries a contact which is normally held open by the action of the magnet. During the passage of the plough the armature is screened and falls back, so completing the circuit and transmitting an impulse.

VEHICLE-ACTUATED CONTROLLERS

Two further necessary definitions are as follows:—

(6) *Demand.*—The effect of an impulse from a detector in a road *not having* right-of-way.

(7) *Extension.*—The effect of an impulse from a detector in a road *having* right-of-way.

The cycle is divided into groups of periods as follows, one group being provided for each phase:—

A $\left\{\begin{array}{l}\text{1. Minimum green period}\\ \text{2. Speed timing period}\\ \text{3. Amber period}\end{array}\right\}$ Phase " A " running

B $\left\{\begin{array}{l}\text{1. Minimum green period}\\ \text{2. Speed timing period}\\ \text{3. Amber period}\end{array}\right\}$ Phase " B " running

This is shown in Fig. 5.

THE TIMERS

General

The timers comprise condenser charging or discharging circuits in conjunction with neon tubes. The theory of this form of timer was described very fully in Mr. Preist's paper,* and the matter given here is supplementary thereto.
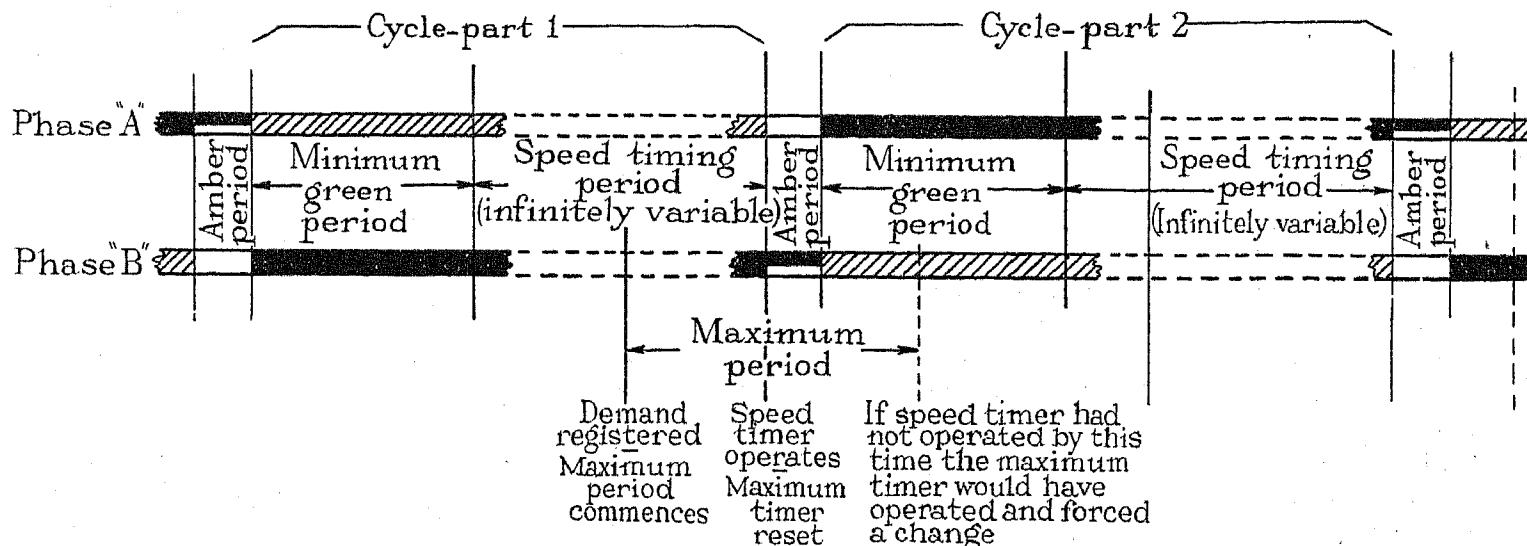

Fig. 5.—Operation cycle of a 2-phase 2-part-cycle vehicle-actuated controller.

Transference of right-of-way normally occurs only when a demand has been registered, and then only in the absence of traffic on the road having right-of-way or on the incidence of a suitable gap between the vehicles.

Immediately after the transfer of right-of-way to a road there follows the " minimum green " period, during which no further change can take place, in order to permit stopped vehicles to start up and pass into the intersection without further detector operation. " Extensions " are afforded to vehicles during the minimum green period and subsequently, and are so arranged as to be approximately inversely proportional to the speeds.

The " amber " period is the clearing time between the right-of-way periods of any two phases. In order to limit the waiting time of stopped traffic to a reasonable duration, extensions are only permitted to continue for a predetermined maximum period following a demand, on termination of which the traffic is arbitrarily interrupted and the right-of-way transferred. When this occurs the right-of-way is automatically restored later to the road from which it has been taken. In addition the amber period, which normally has to protect only vehicles already in the intersection, is specially extended by 2 sec. to protect the arbitrarily interrupted traffic which cannot pull up at the " stop " line.

The " maximum " period commences on the registration of a demand at any time after the amber period. This period has been known up to the present time as the " maximum green period," but it is suggested that this term should ultimately be replaced by a more suitable one which conveys the meaning " maximum green period after registration of a demand." The term " maximum green period " is misleading, and the green indication may, of course, show indefinitely to one road in the absence of traffic on the other.

Briefly, a condenser is charged or discharged through high-value resistances, and the period of time for a
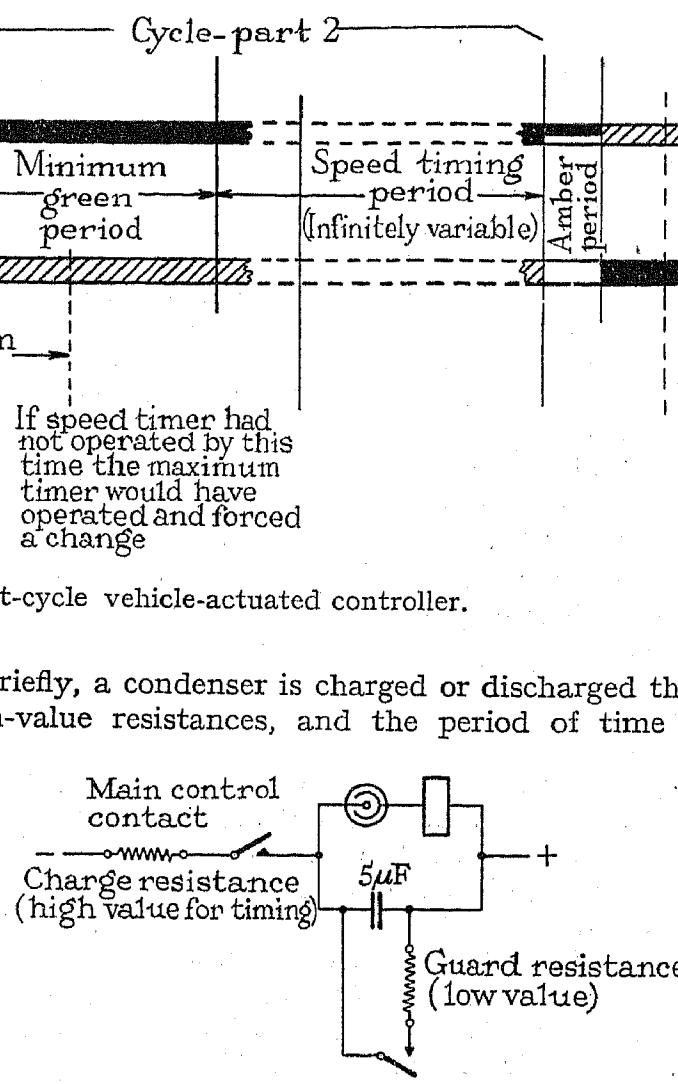

Fig. 6A.—Basic circuit of " charge " timer.

change of potential of any value can readily be calculated. Neon tubes have the property of acting as almost perfect insulators until the neon gas is ionized (when the tubes are said to " strike "), when they become good conductors
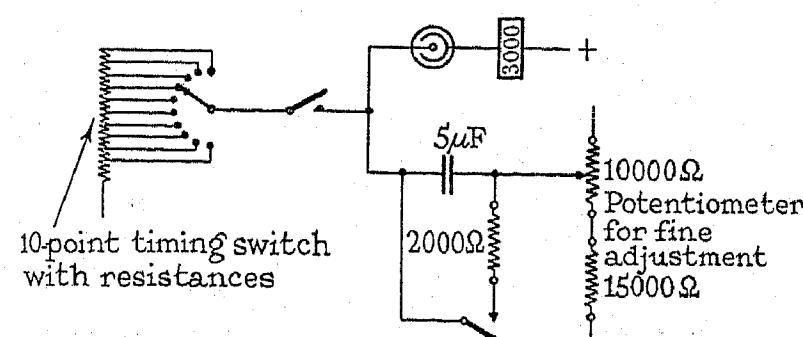

Fig. 6B.—Developed " charge " timer.

capable of passing sufficient current to operate relays. For tubes in regular use the ionizing potential varies but

* See Bibliography, (1).

little, and it can be seen that such tubes provide a ready means not only for indicating when a required difference of potential is attained but also for effecting any desired switching change.

The circuits of two arrangements are shown in Figs. 6A and 7A. In the former the tube is connected in parallel with the condenser so that it can determine when the
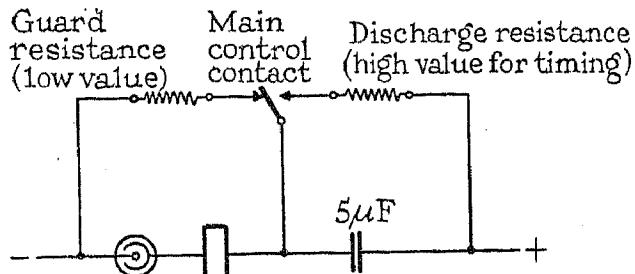

Fig. 7A.—Basic circuit of " discharge " timer.

required degree of charge has been reached, while in the latter it is connected in *series* with the condenser so that it measures the *difference* between the main supply potential and the potential existing across the condenser. The latter circuit was developed largely with a view to ready adjustment, to cater for variations in striking voltage of the commercially-produced tubes, and the inclusion of a potentiometer for this purpose was found an easier matter than with the charging arrangement (see Figs. 7c and 7D).

One defect of the discharging arrangement is that the tube strikes immediately the apparatus is connected to a supply. This is, however, of no moment except in alarm circuits in progressive master controllers (described later), and research has now led to the development of a simple charging timing circuit which includes a potentiometer (see Fig. 6B).

When the tube strikes, current passes through the tube and relay, and the condenser is discharged or recharged as the case may be. After a brief interval this current ceases, the tube is extinguished, and the relay falls back. The average duration of the impulse is 80 millisec. The


Fig. 7B.—" Discharge " timer: explanatory diagram.

general operation of the discharge timer is shown in Fig. 7B. The more important constants of the timing circuits are given in Table 1. The normal condenser capacitance is $5 \mu F$; V_s is the striking potential of the tube.

The neon tubes are graded according to their nominal striking voltages. Three main voltages are available, namely 250, 170, and 147 volts. The conductivity of the


Fig. 7c.—Developed circuit of " discharge " timer (original form).

higher-voltage tubes is greater than that of the low-voltage tubes, and with them more heavily-loaded relays can be utilized, but these tubes necessitate the use of higher applied voltages, which require superior insulation.

Table 1

Timing resistance (ohms per sec.)	Timing-circuit applied potential (volts)	V_s expressed as a percentage of the applied potential
100 000	$1 \cdot 16 \times V_s$	86·5
200 000	$1 \cdot 58 \times V_s$	63·2
300 000	$2 \cdot 05 \times V_s$	48·8
400 000	$2 \cdot 54 \times V_s$	39·4

The Speed Timer

The conditions of operation of the speed timer differ from those of the normal timer inasmuch as variable times have to be measured off in place of fixed periods. The condenser is normally in the discharged condition,


Fig. 7D.—Developed circuit of " discharge " timer (latest form).

and is charged only when right-of-way is actually required, i.e. when an approaching vehicle crosses a detector and operates the right-of-way relay; and the neon-tube circuit is not completed until the registration of a demand. Curves showing the performance of the speed timer and the relationship of the vehicle speeds to

the impulses delivered are reproduced in Figs. 8 and 9. The high-speed relay which is used to repeat the vehicle impulses has remarkably small operating and releasing times, of the order of 0·5 millisec., so that extreme accuracy is obtained. A range of discharge resistances is provided to suit intersections of various sizes.

It is of interest to note the various methods of measuring the vehicle impulses. The first tests were made by means of an oscillograph, but this method had disadvantages for repeated use. The Siemens millisecond-meter was also used extensively, but this gave no permanent record and was not sufficiently accurate when measuring each of a train of impulses such as those due

which is used in modern automatic telephone exchanges (see Figs. 10A, 10B, 10C, in Plate 1, facing page 134). The pillar has no permanent equipment other than the main switch and fuses to terminate the supply mains, as the whole of the operating equipment is carried on the controller framework which is placed in the pillar.

An important feature is that the whole of the switching is effected by means of relays. Apart from the relays the equipment is purely static, with the single exception that a dynamotor is necessary when the supply is direct-current. In a.c. systems power is obtained from a transrecter, which includes a transformer, rectifiers, condensers, and fuses. The dynamotor includes three arma-
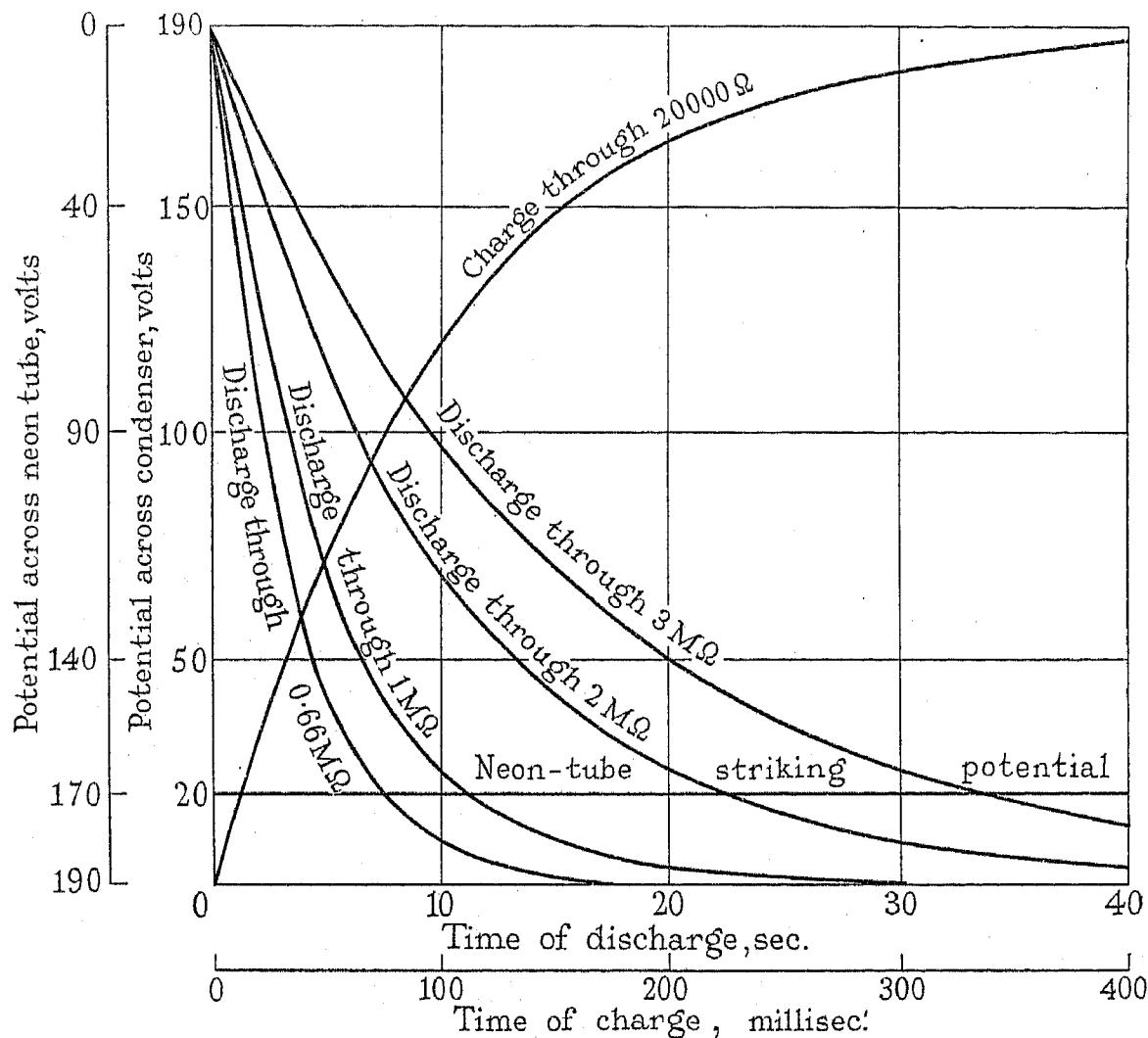

Fig. 8.—Principle of the speed timer.

to a six-wheeled vehicle. A very satisfactory method, but only possible in a laboratory, was that of trailing electrodes over a revolving recording paper which had been rendered conducting and sensitive to polarity by soaking in a solution of phenolphthalein. A 50-cycle timing wave was connected to one of the electrodes.

CONTROLLER CONSTRUCTION

The 2-phase controller was originally accommodated inside a specially-constructed signal post, but owing to the ever-increasing proportion of multi-phase and progressive controllers this type has now been abandoned. A larger type of pillar which was previously reserved for the latter is now being used for the simpler controllers also. The controller is built up on an open iron framework on the well-known demountable unit principle

ture windings and commutators on one shaft, and fuses are mounted on the unit.

The more recent power units (both a.c. and d.c.) include equipment for stabilization of the H.T. voltage.

Two sizes of controller are available, known as "standard minor" and "standard major" controllers. Fig. 10A gives a general view of the standard minor controller assembly. It will be seen that shelf positions are provided for main and auxiliary relay sets, a power unit, and a neon-tube unit, and by fitting appropriate units any control scheme can readily be provided. Fig. 10B is a rear view showing the wiring, and Figs. 11A, 11B, 11C (see Plate 2), are views showing controllers equipped for various typical control schemes.

At the top of the framework is the timing control panel, and this also is designed with a view to great variability of

facilities. Accommodation is provided for 14 rotary timing switches, this being sufficient for any isolated controller having up to four main phases and a special facility. Accommodation is also provided for a large number of high-value resistances. The main wiring of the framework is standard for all control schemes, but the control panel is connected by means of jumper wiring to suit the facilities required (see Fig. 10c).

The relays are of the most modern telephone type, all except the high-speed relays used to repeat the vehicle

"twinned." The overall dimensions of the relay are 4 in. $\times$ 2$\frac{1}{4}$ in. $\times$ 1 in.

The circuit arrangement is shown in Fig. 13. When springs Nos. 2 and 3 are opened the current is diverted to the condenser, and becomes reduced. The impedance then enables springs Nos. 2 and 1 to be opened with safety, and in actual practice the spark is barely visible when the lamp load is as high as 3 amperes at 250 volts. Normal time-lags on the contact are ample for charging the condenser.
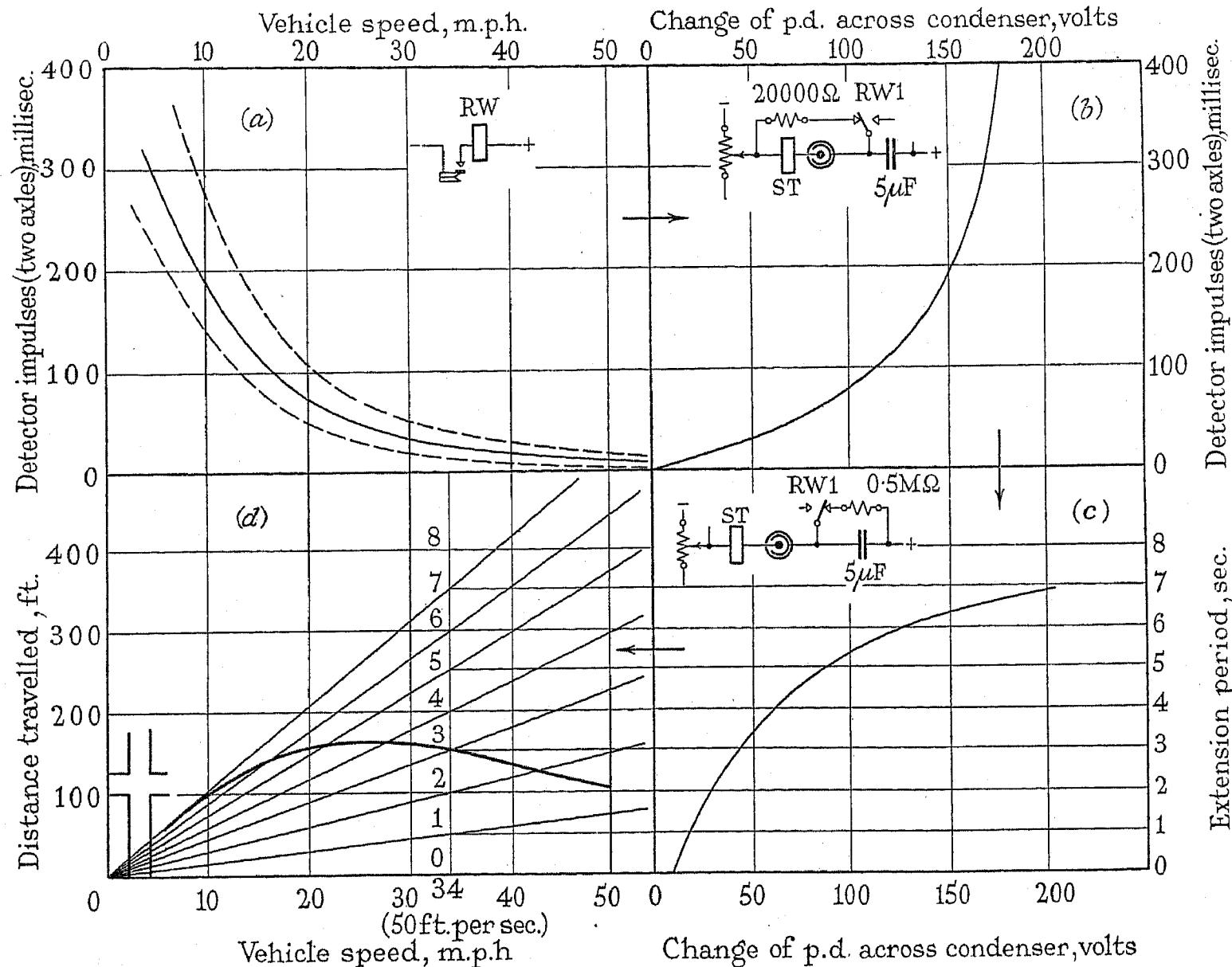

Fig. 9.—Speed timer: typical performance.

(a) Vehicle crosses detector; impulses passed to controller. (The impulses corresponding to the various speeds may vary within limits indicated by dotted lines, owing to weight of vehicle, degree of inflation of tyres, angle of approach, etc.) (b) Condenser charges for duration of impulses. (c) Condenser discharges, so measuring off extension period. (d) Distance travelled by vehicle during extension period.

impulses being similar to the Post Office standard Type 3000. The essential difference between P.O. relays and those used in traffic controllers is that the latter are specially insulated to pass a 1 000-volt insulation test.

THE LAMP CONTACTORS

By the use of a special arc-quenching arrangement it is possible to use telephone relays for control of the main signal lamps. A typical contactor is shown in Fig. 12, from which it can be seen that each action comprises three springs fitted with large contacts operating in sequence. This particular relay includes both ordinary and power contacts. The ordinary contacts are

THE TWO-PHASE CONTROL SCHEME

Fig. 14 shows the general principles of the 2-phase control scheme, and Fig. 15 indicates the basic circuit.

The detectors associated with the roads having right-of-way are connected by means of the road-connecting relay to the right-of-way relay, and the detectors associated with the other roads are similarly connected to the demand relay. The lamp-control and road-connecting relays work together and ensure the correct relationship of the road relays and signal lamps. The right-of-way relay repeats the vehicle impulses to the speed timer, which extends the right-of-way periods according to the speeds. When a vehicle passes over a mat in a closed
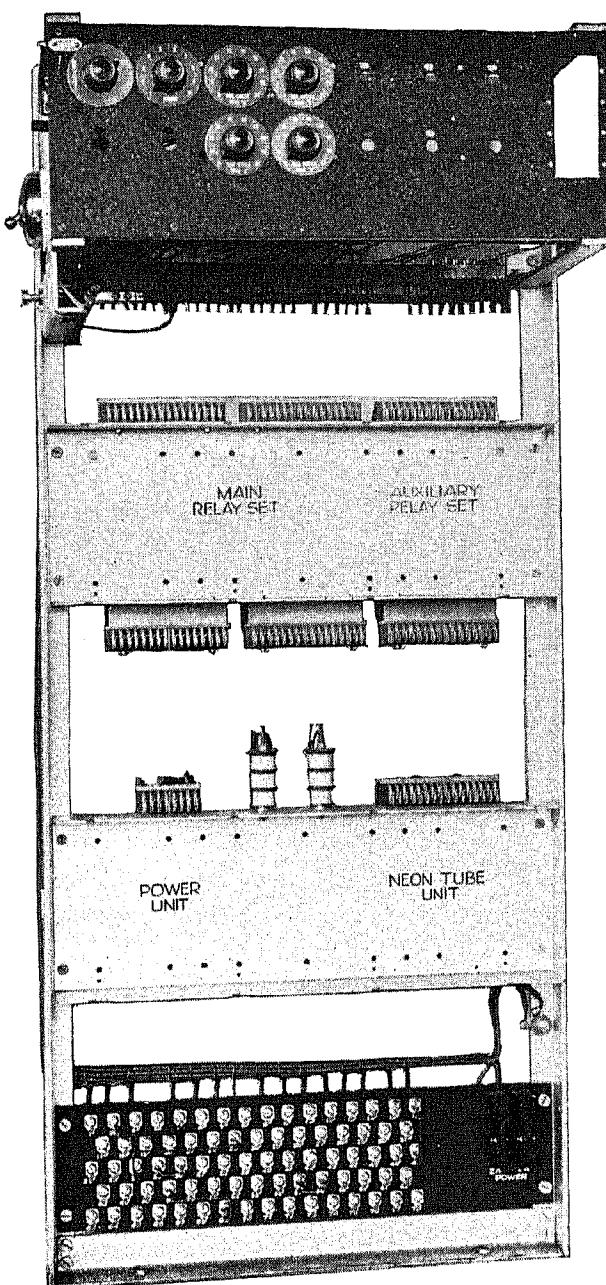
Fig. 10A.—Standard minor controller, unequipped, front view.
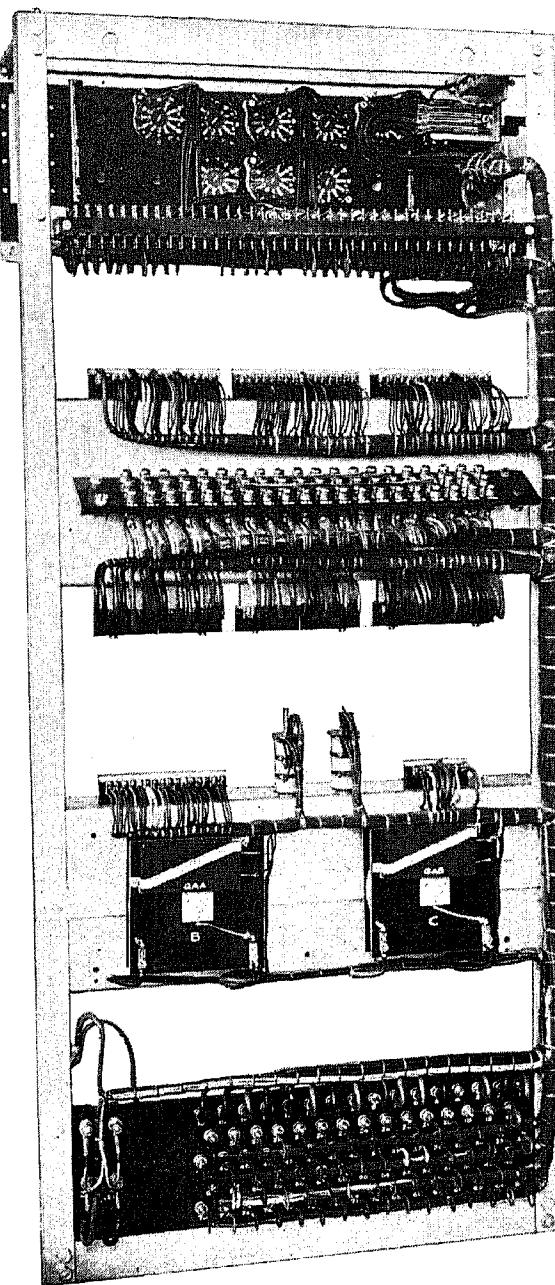
Fig. 10B.—Standard minor controller, unequipped, rear view.
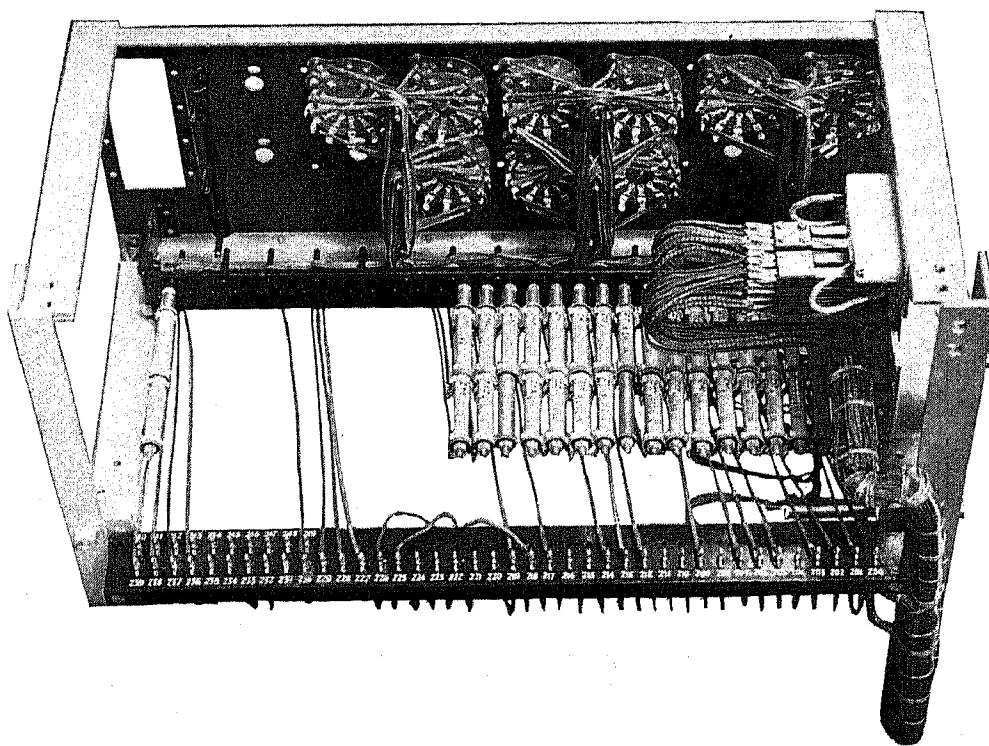
Fig. 10C.—Standard minor controller: control-panel jumpering.

Plate 2
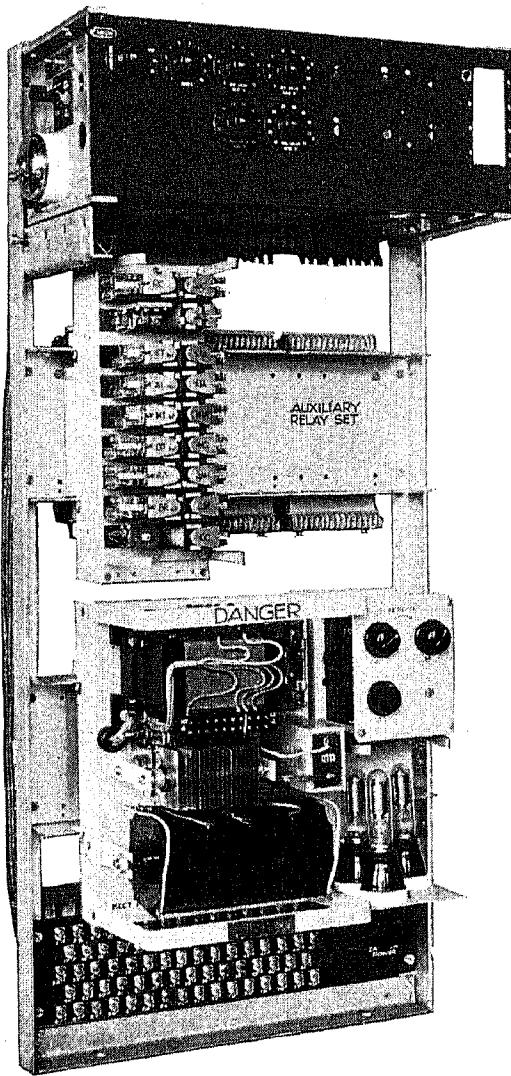
Fig. 11A.—Standard minor controller, 2-phase isolated, for a.c. operation.
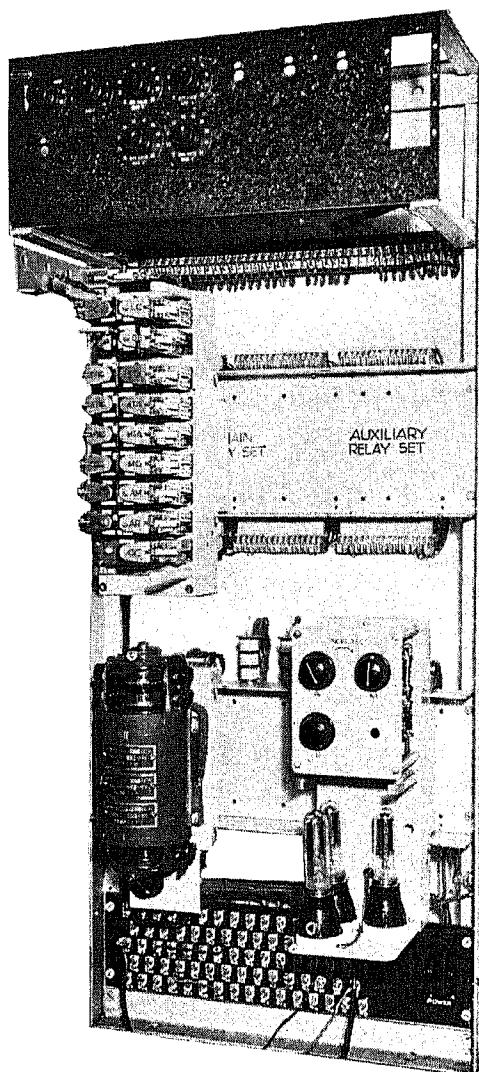
Fig. 11B.—Standard minor controller, 2-phase isolated, for d.c. operation.
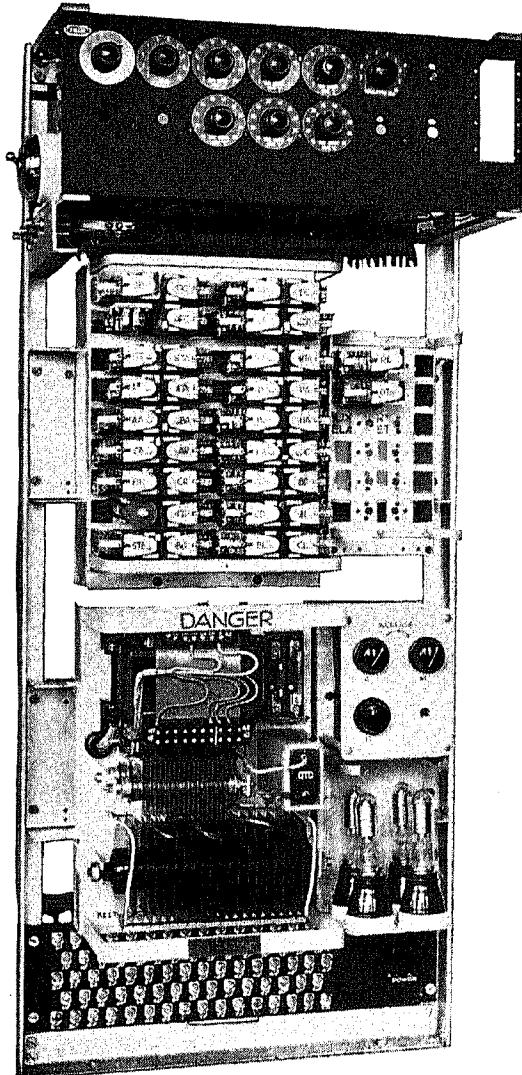
Fig. 11c.—Standard minor controller, 3-phase isolated, for a.c. operation, with overlapping red.

road the demand relay operates and locks, indicating to the speed timer that a change-over is required. On expiration of any existing extensions the speed timer sets up change-over conditions and operates the change-over
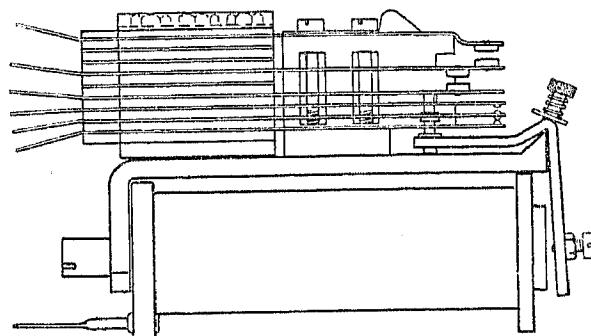

Fig. 12.—Typical relay (contactor).

relays. If a continuous stream of traffic is passing, the maximum green timer forces the speed timer to effect a change-over when a predetermined period has elapsed after registration of the demand. The maximum green
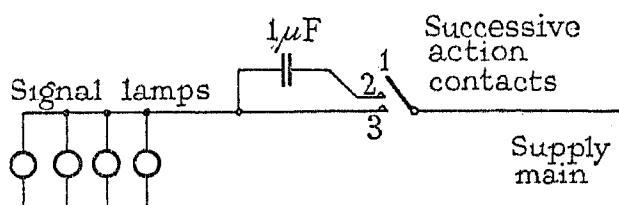

Fig. 13.—Contactor arc-quench circuit.

timer prevents the speed timer from releasing the demand relay, in order that the right-of-way shall be returned to the interrupted road, and also indicates to the amber timer that a lengthened amber period is required. The
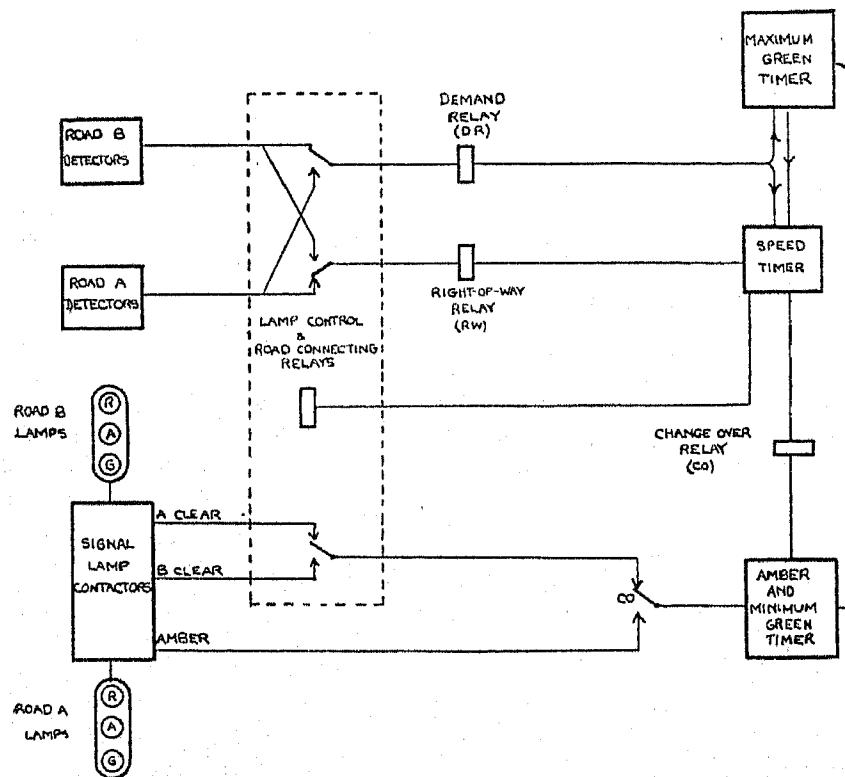

Fig. 14.—General principles of 2-phase controller.

speed timer changes the setting of the road-connecting and lamp-control relays.

The change-over relays extinguish the green lamps, connect the amber lamps, and cause the amber period to be measured off by the amber timer. On expiration

of the amber period the amber timer is used a second time to measure off the minimum green period, after which the process is repeated as required.

MULTI-PHASE VEHICLE-ACTUATED CONTROLLERS

The application of vehicle-actuation to multi-phase control schemes involves considerably more complexity than is associated with fixed-time controllers. This must not, however, be regarded as a disadvantage, as the added complexity is merely due to the remarkable flexibility of operation which becomes available with vehicle-actuation.
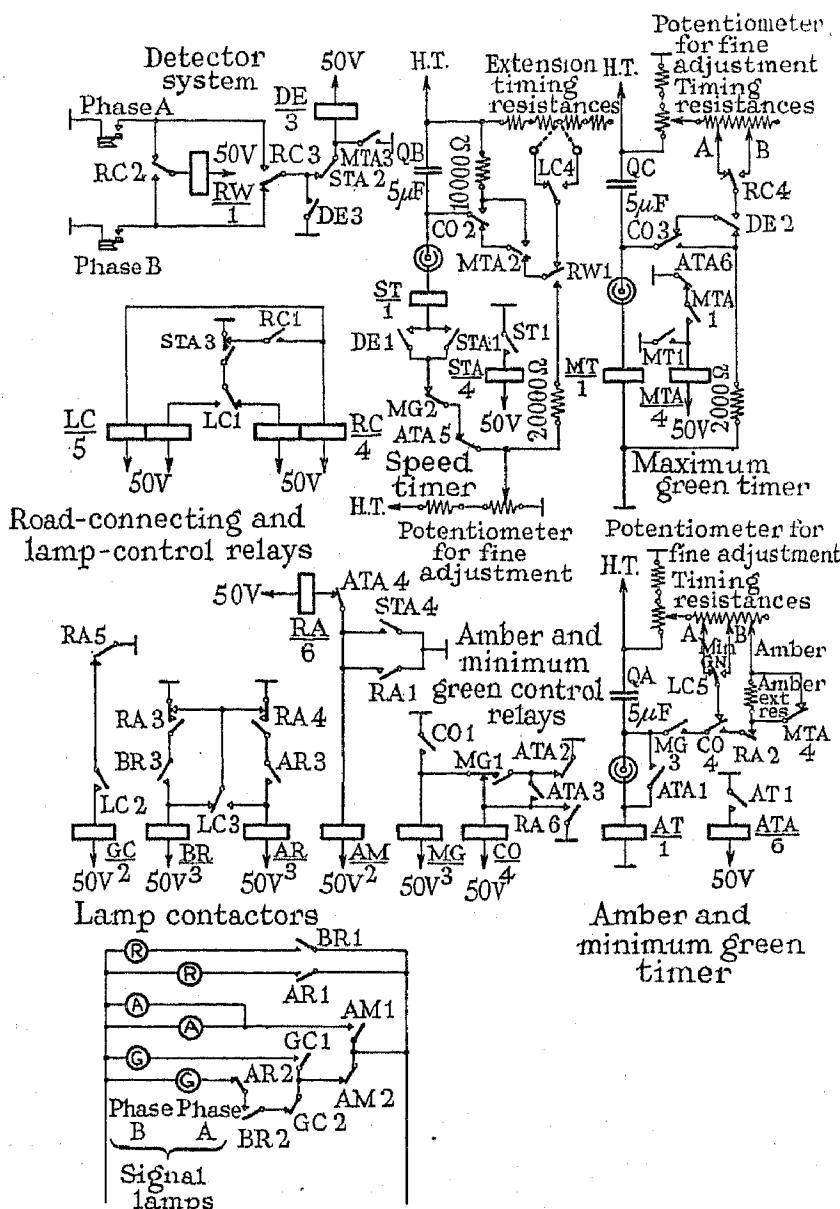
Fig. 15.—Basic circuit of 2-phase controller.

With fixed-time operation the function of the controller is just the regular subdivision of the cycle into definite right-of-way periods for the various roads, always in the same order. Multi-phase controllers must be capable of varying the durations of the right-of-way periods to suit the traffic, as in the case of 2-phase controllers, and also of omitting unwanted cycle-parts in the absence of traffic, at the same time maintaining the standard signal sequence when transferring the right-of-way from any one phase to any other. There is also the question of whether the right-of-way should be transferred in the order in which demands are registered ("first come, first served "), or in a definite cyclic order (" fixed rotation ").

Relays formed a ready solution to these problems. With the all-relay controller the normal simultaneous amber sequence was easily arranged: also from the earliest examples the controllers have operated on the " first come, first served " principle when required.

The general scheme of the " first come, first served " controller is shown in Fig. 16. Demands for right-of-way are stored and given attention in order of arrival, except on operation of the maximum timer, when the controller deals with the phases in straightforward alphabetical order.

Each phase has associated with it a " road circuit " containing a " demand " relay and a " lamp " relay. When a road has right-of-way its " demand " relay is disconnected and the detectors are connected by means of the " speed timer connector " to the " right-of-way " relay in the " speed timer circuit." The " lamp " relay

Three- and four-phase controllers differ only in the number of relays and timing switches provided.

The " fixed rotation " controller operates in a similar manner, except that searching does not take place until *after* the speed timer has operated.

There is one misleading effect associated with the " first come, first served " controller, in that one phase is sometimes given right-of-way twice before another road having a stored demand receives attention at all. This is due to reversal of the direction of rotation when a change-over occurs from " first come, first served " to " fixed rotation " working when the traffic increases in intensity, as in the following example.

Assume that right-of-way is actually on Phase " B," and that the marker indicates that the next phase to receive right-of-way is " A." There is also a demand on Phase " C," so that the controller is rotating in reverse
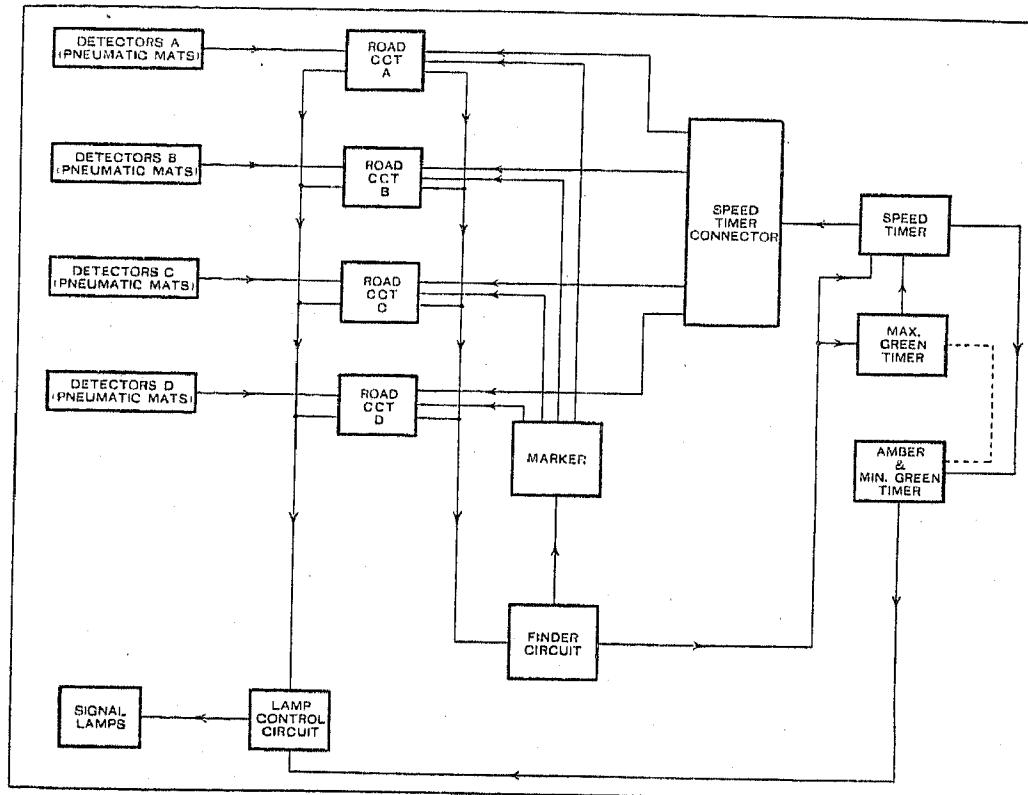

Fig. 16.—General principles of multi-phase controller.

controls the signal-lamp contactors. The main functions of the right-of-way relay and the various timers are the same as in the 2-phase controller.

When a vehicle passes over a mat in a road not having right-of-way, the " demand " relay operates a " start " circuit, which indicates to the " marker " circuit and to the speed and maximum-green timers that a change-over is required. The marker proceeds to hunt over the road circuits until it finds the calling road. When the change-over takes place the speed timer releases the speed-timer connector relays, which immediately reconnect themselves to the road circuit indicated by the marker. The marker is then free to hunt for further calling roads. If demands are registered in two or more phases simultaneously, the controller deals with them in alphabetical order, commencing with the road immediately after the one having right-of-way. The marker cannot connect itself to more than one road circuit at a time. The remainder of the operation is similar to that of a 2-phase controller.

order, thus: C—B—A—C. Next assume that the traffic becomes heavy on Phase B. The fact that B is arbitrarily interrupted entails automatic reversion to that road. As the finder does not commence a fresh search until the demand on A has received attention, and as it searches in alphabetical order it finds B's revertive demand before C's normal demand. The sequence then becomes as follows: C—B—A—B—C. Rotation continues in alphabetical order as long as the maximum timer continues to operate.

If the controller had been rotating in alphabetical order, owing to the fact that the traffic happened to have arrived in that order, then there would have been no reversal of rotation.

TRAFFIC RESPONSE TO " FIXED ROTATION " AND " FIRST COME, FIRST SERVED " CONTROLLERS

A number of both types of controller have now been in operation for long periods, and as a result it is possible

to state the principal conditions for which each is best suited. Traffic-control schemes for unusually complex intersections are frequently planned to have the cycle-parts following one another in such a manner that the starting vehicles fit in with the clearing vehicles of the stopping phase with a minimum of interference, and if the phases were taken out of order at times of heavy traffic serious congestion might result. In this case the "fixed rotation" controller is obviously preferable. When the control scheme includes a pedestrian phase the "fixed rotation" controller is again desirable. The pedestrians should be given right-of-way immediately after the main phase, as otherwise they cross out of their turn and
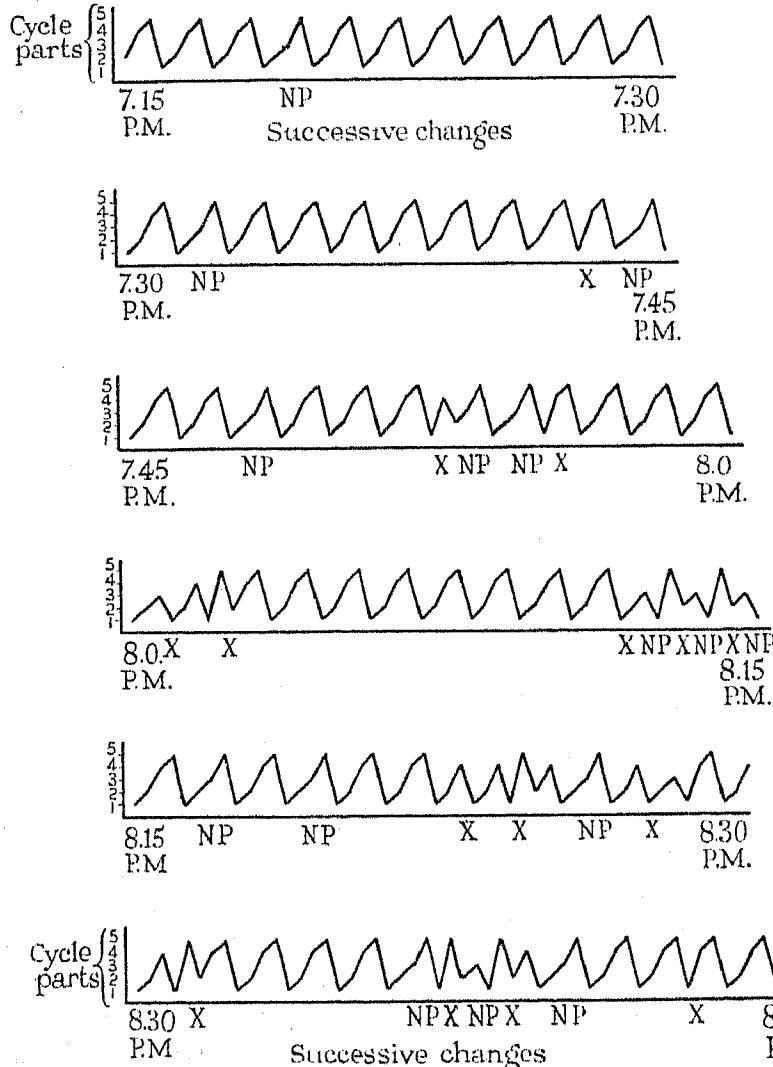

Fig. 17.—Diagram showing actual sequence of cycle-parts at a "first come, first served" multi-phase controller.

NP No pedestrian pressed a button during these cycles.
X Non-cyclic order.

controllers, and associated with one particular phase only, namely the second choice away from the main traffic phase. Vehicles in this unfortunate phase register their demands and complete the vehicle and maximum timer circuits in the usual manner. Assume that the main traffic flow is heavy, and that no gap in the traffic stream occurs before operation of the maximum timer. Assume now that a vehicle arrives in the first-choice
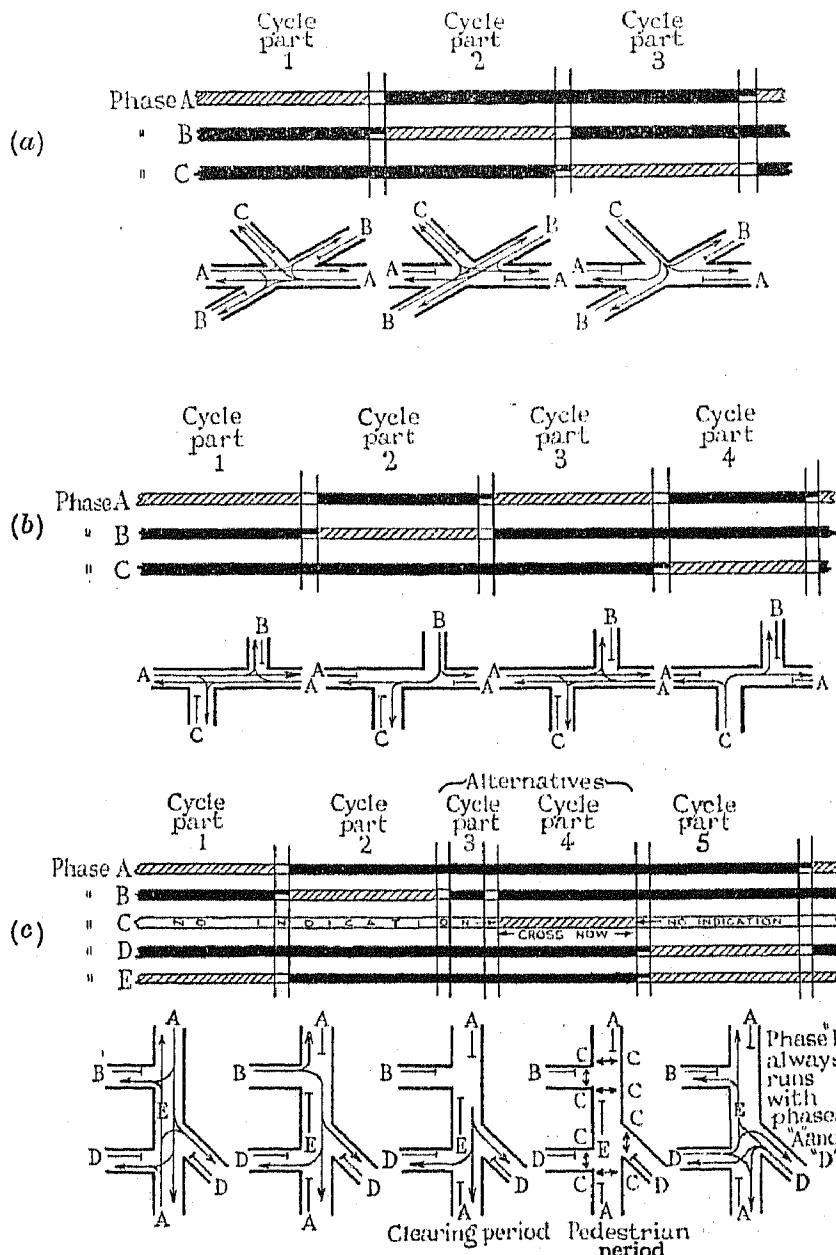
Fig. 18.—Examples of multi-phase control schemes.
(a) Normal 3-phase 3-part-cycle scheme.
(b) Three-phase 4-part-cycle scheme.
(c) Special 5-phase 5-part-cycle scheme.

obstruct the side-road traffic. For all other cases the "first come, first served" controller is preferable.

The principal advantages of "first come, first served" control are that delays are minimized, particularly at times of light and medium traffic; and that the most suitable methods for different densities of traffic are available. Drivers are more likely to be satisfied if they are taken in their turn, without long delays when the traffic is light; while, as the controller changes to fixed rotation with heavy traffic, the system is also suitable for schemes of a complex nature.

The author has from time to time received complaints from drivers regarding consistently long delays at certain intersections. On investigation these delays have been found to be at intersections controlled by fixed-rotation

phase just before the end of the maximum period. The maximum timer operates, and the vehicle which has just arrived is given right-of-way immediately, while the traffic in the second-choice phase has to wait through a further period. It will be seen that the first effect of the first demand is merely to operate the maximum timer in favour of other traffic.

An examination has been made of the performance of a number of multi-phase controllers, and it has been found that the "first come, first served" feature virtually does not exist when the traffic is heavy. The controller quickly accommodates itself to "first come, first served" operation when the traffic is suitable, and as quickly reverts to fixed-rotation operation if the decrease in the traffic is only temporary. This is apparent on examina-

tion of Fig. 17, which shows the actual order of the cycle-parts at the 5-phase 5-part-cycle controller installed at Streatham Hill Station during the period of decreasing traffic from 7.15 p.m. to 8.45 p.m. Further details of the control scheme are shown in Fig. 18(c), and it should be explained that Cycle-part 3 (overlapping red) is arranged to occur after Cycle-part 2 except when the pedestrian phase is the next to receive right-of-way. The characteristic shape of the curve can readily be recognized and irregularities can be picked out.

THE PROBLEM OF RIGHT-HAND-TURNING TRAFFIC

It was stated in the paper by F. L. Castle and F. Horler* that the right-hand turn was *the* problem. Although a number of methods of dealing with right-hand-turning traffic have been devised for cases where this inconvenient movement occurs with great frequency, the problem still remains, and it is probably true to state that the major proportion of delays are due to this cause. The problem is particularly apparent in narrow streets and in progressive signal systems.

The principal signalling methods by which congestion due to right-hand-turning traffic is minimized are as follows:—

(a) Full 3-phase signalling, the phase with the preponderance of turning traffic being signalled alone.

(b) Early cut-off signalling. This involves running the two relevant roads simultaneously as in ordinary 2-phase signalling, and then stopping the normally loaded road early while the opposite road is permitted to run for an extra period to clear the accumulated traffic waiting to turn to the right.

(c) Late-start signalling. This involves starting the road having the preponderance of right-hand-turning traffic a few seconds before the opposite road is given right-of-way, so enabling the former to establish itself physically in the intersection for as long as may be necessary.

The various methods are shown diagrammatically in Fig. 19. The examples given apply more particularly to ordinary crossroads or T-junctions, and it will be seen that the numbers of phases and cycle-parts are both 3 instead of the customary 2 for such intersections.

An auxiliary relay set is "jacked-in" alongside a normal main relay set. Two additional timing switches are necessary for the early cut-off facility (maximum extended period and minimum extended period), and one for the late-start facility (late-start delay period). A switch is provided to enable the facility to be cut in or out at will to cope with seasonal traffic, and there are cases where external controls, such as tramway point levers and other tramway detectors, have been connected in parallel with this switch to cater for unusual movements on the part of tramcars. The facilities can equally be applied to 2-phase and to multi-phase controllers.

A disadvantage of the early cut-off arrangement is that there is a waiting period for traffic which is approaching red signals in the independent phase, as the controller has to pass through the special sequence before giving right-of-way to this phase. The only manner in which this can be completely avoided is by providing separate

* See Bibliography (3).

lanes for the right-hand-turning traffic, complete with detectors in such positions that it is made impossible for the special detectors to be traversed by non-turning traffic. The special detectors may be used to register a demand for the early cut-off period or special cycle-part.

It is of interest that the development of the early cut-off facility included what was probably the first application of the theory of probabilities to street traffic problems. The method of operation which was supported by use of this theory was that, as the right-hand-turning phase is assured of additional right-of-way time *after* each change-over has commenced, there is no necessity for traffic in that phase to be detected when the early cut-off phase has right-of-way, and that only during the extended
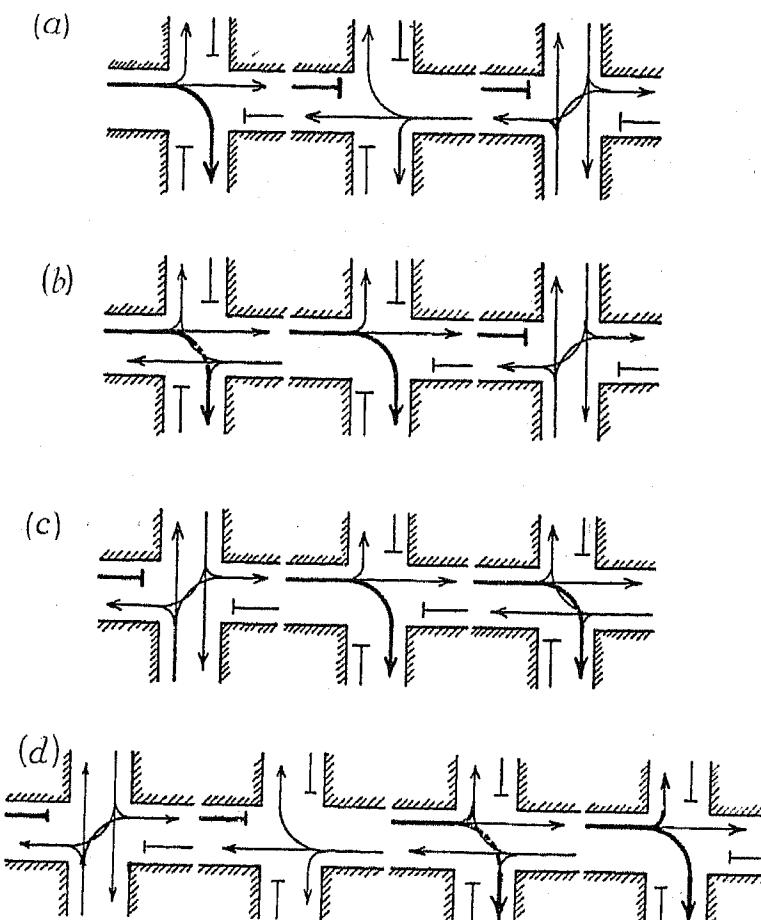
Fig. 19.—Methods of dealing with a preponderance of right-turning traffic.

(a) Full 3-phase.
(b) Early cut-off.
(c) Late start.
(d) Late start and early cut-off combined.

period should the right-turning traffic be speed-timed. The net result is that the waiting time of the traffic in the independent phase is kept to an absolute minimum, as a gap in the traffic in only one road and not two has to be awaited before the change-over commences.

As an example, let it be assumed that the total traffic in the normal and early cut-off phases is 1 800 vehicles per hour, and that vehicles require an average time of 6 sec. to clear the intersection. The probability of the favourable condition occurring is given in Table 2 for various proportions of traffic in each direction.

The probability of a gap occurring in both phases simultaneously is 0·0498 (incidentally this is the figure for normal crossroads). Thus, when the traffic is the same in each direction the condition favourable to such a change occurs about 4·5 times as frequently with the

arrangement described as it would if the traffic in both directions were considered. In the extreme case of 90 % of the total traffic arriving along the right-hand-turning phase, the favourable condition occurs 15 times as frequently.

One untoward condition which tends to occur at some intersections having early cut-off control is that the right-turning traffic passes into the intersection and establishes itself, thereby sometimes causing congestion in the opposite phase. This can be alleviated by the use of both late-start and early cut-off features together [see Fig. 19(d)]. The late-start feature is used in this case not for its normal function of permitting the right-turning traffic to establish itself, but instead to enable the opposite phase to establish itself, the right-turning traffic being assured of adequate time to clear during the subsequent early cut-off period. The two opposite roads might then be described as being " slipped " in phase relationship.

CLEARING PERIODS

The inter-cycle-part clearing periods need to be of varying durations to suit the diverse traffic conditions

Table 2

Traffic density (vehicles per hour)		Probability of condition for effective demand
Normal phase	Early cut-off phase	
1 620	180	0·741
1 440	360	0·549
1 260	540	0·406
1 080	720	0·301
900	900	0·223

and intersection shapes to which signal systems are applied. Long amber indications have a disconcerting effect on drivers, and the longest amber indication should not exceed approximately 5 sec. When longer clearing periods are required they are provided by means of either the " consequent amber " facility or the " overlapping red " facility; these are illustrated in Fig. 20. The former entails the occurrence of the leaving and starting amber periods of the affected phases one after the other, while the second is similar but has in addition an intermediate period during which all signals at the intersection show red. The facilities are again provided by the addition of an auxiliary relay set.

Overlapping-red clearing periods are sometimes put under the control of the traffic in the restricted area and have varying durations according to the time taken by the traffic to clear. In the absence of traffic in the restricted area the period can automatically be shortened down to the duration of the normal amber period. This facility finds particular application in cases of narrow bridges, though there are other instances where it has usefully been applied, as, for example, in the narrow streets of some old-world towns.

The author has adopted the expression " overlapping red " in preference to the expression " all red " which is

sometimes employed, as it is felt that the latter can usefully serve to describe another state which is not so transitory in nature—the switching of all the signals to red manually to hold up the traffic for processions, fire engines, etc.

OTHER SPECIAL FACILITIES

The schemes so far described are the main ones in use, but there are also many examples of special control schemes developed for particular intersections. The adaptability of the equipment is such that the provision of special features is not a difficult matter, and in actual practice the number of special control schemes forms an ever-increasing proportion of the whole.
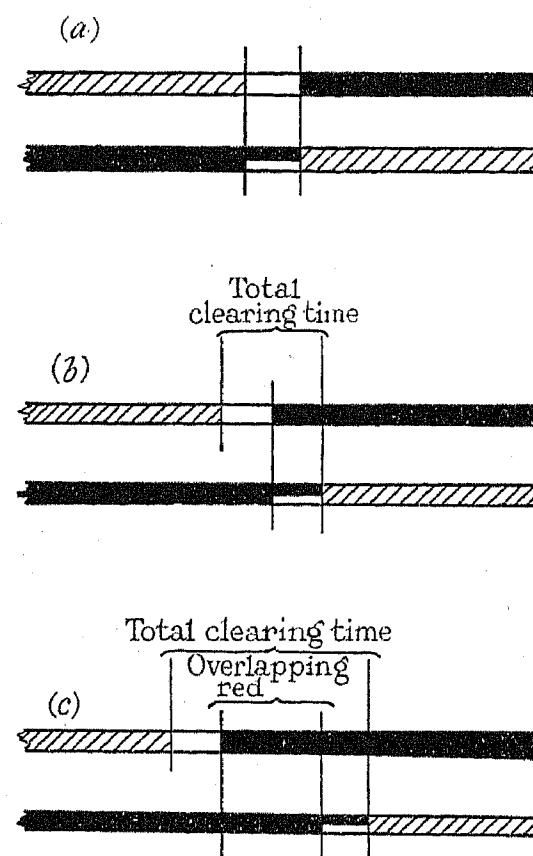
Fig. 20.—Clearing periods of various durations.

(a) Normal amber period.
(b) Consequent amber periods.
(c) Overlapping red period.

FLEXIBLE PROGRESSIVE SYSTEMS

A flexible progressive system is a multiplicity of " local " traffic controllers, one at each intersection throughout the controlled area, electrically linked to one " master " controller which serves to co-ordinate the indications given to the traffic. From the most elementary point of view the signals in such a system may be regarded as changing to green and back again to red in such a manner that the green lamps appear to be travelling along the road. Actually the problem is not as simple as this, for the traffic streams in the two opposite directions both have to be provided with facilities for a smooth flow, and, in addition, all cross traffic must be given frequent and adequate opportunities to proceed. A " time-and-distance " diagram has first to be constructed, and from this the various controllers are adjusted.

"Time-and-Distance" Diagrams

Typical time-and-distance diagrams for a hypothetical progressive system are depicted in Fig. 21. The street is reproduced to scale on the left side except that all curves have been straightened out. A time scale has been constructed along the lower edge of the diagram.

The traffic is divided into trains or convoys, each containing as many vehicles as can enter the system while the signals at the first intersection remain green, and these trains are represented by means of the sloping bands. The narrow horizontal bands show the main road signal indications (without vehicle actuation) at the various intersections.

It can be seen that one of the essentials of the system is that the "cycle time," i.e. the time of one complete

(a) Controllers operated by constant-speed synchronous motors from the one set of a.c. supply mains but otherwise unlinked. The controllers were adjusted locally to be in correct phase relationship with one another and no remote control of the timing was possible.

(b) Reference points of the cycle indicated to the local controllers by change of energization of tie lines by means of a master controller. The controllers in this system also were adjusted locally. Such a system is in use in Oxford Street, London, and as this system has had to be connected by junction circuits with one of the new vehicle-actuated progressive systems further details of it will be given later.

(c) "City Hall" systems, in which the control of the whole of the signals in the city is located at a central
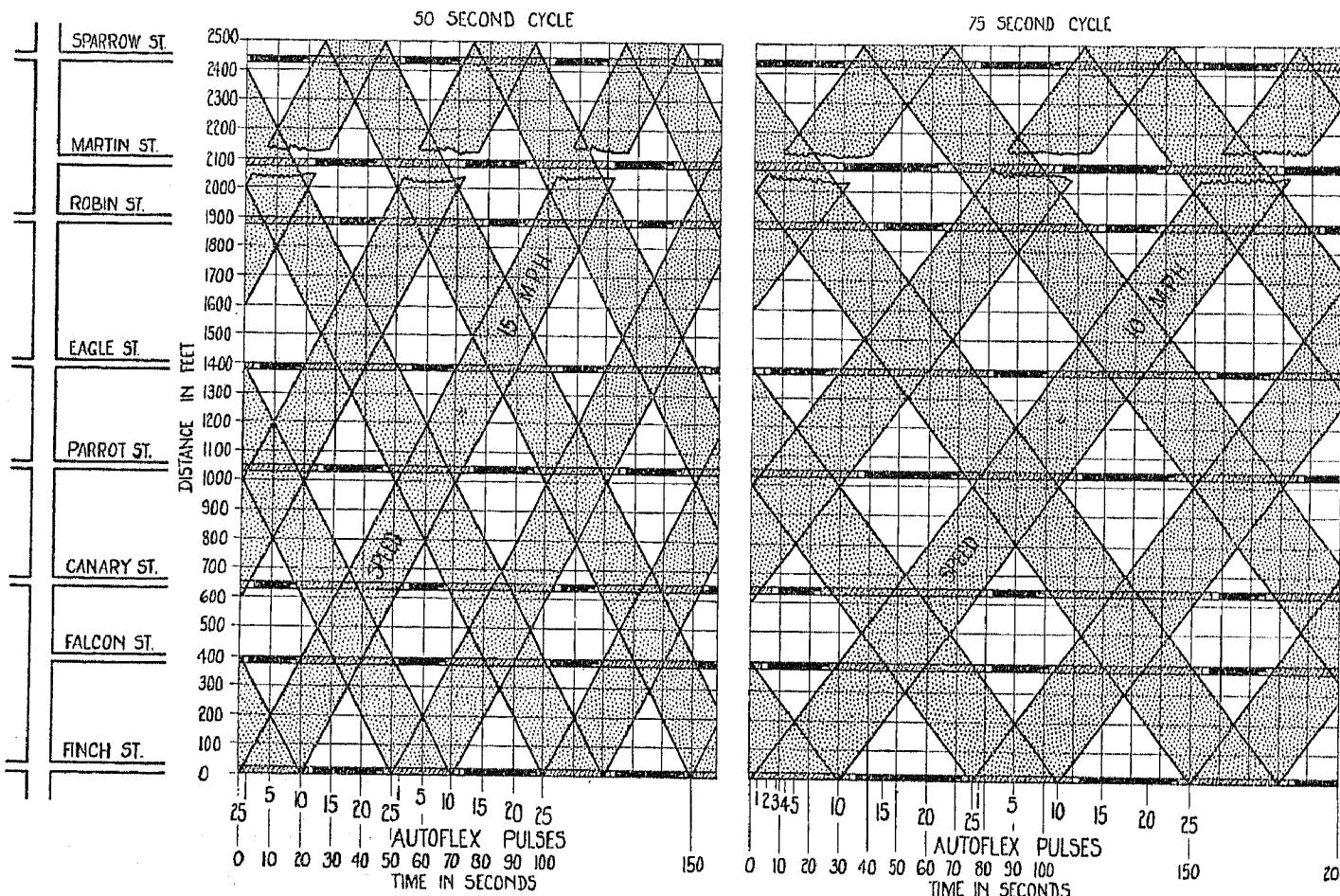

Fig. 21.—Typical time-and-distance diagram.

cycle of events as indicated by the sum of the red and green indications on any signal, must be the same at all intersections, and this is automatically ensured by means of the master controller.

The speed of the traffic is shown by the slope of the traffic band, and by comparison of the diagrams for 50-sec. and 75-sec. cycles it can be seen that the speed is inversely proportional to the cycle time. The band width varies with the cycle time. The diagrams for the various cycle-times are fundamentally "concertina" replicas of one another.

For the most efficient working, long cycle-times are desirable when the traffic is dense, and short cycle-times when the traffic is light, on account of "headway" and starting time.

Of early flexible progressive systems there were many types, notably in America. The most important instances were:—

station. Examples of these are to be found in Chicago, Berlin, and Amsterdam. Frequent manual readjustment of the timings is possible by this method, but the cost of installation and operation is high compared with that of other systems. The system installed in Amsterdam is very comprehensive in nature, and is designed on telephone principles.

A Typical Fixed-time Flexible Progressive System

The principles of this system are shown in Figs. 22A and 22B. The controllers each incorporate a shaded-pole induction motor with a camshaft. The tie lines are common to all the controllers and are four in number, namely an "A" wire, a "B" wire, a remote-control wire, and a common-return wire. The "A" wire is energized for one half of the cycle and the "B" wire for the other half. The induction motors have three windings, the first and second capable of being energized from

the " A " and " B " wires respectively. Immediately either wire is energized the motor runs for a predetermined time, then operates cam springs which change over the main windings, so leaving both de-energized, and energize the third winding, which runs the motor for the duration of the amber period. At the end of the amber period, cam springs are again operated, the signals are changed over, and the motor comes to a standstill until the tie-line energization is next reversed.

The motor speed is set by the positioning of certain pole-pieces. The motor running time, having thus been predetermined, remains the same whatever the cycle time.

It is perhaps necessary to explain that Figs. 22A and 22B relate to the system installed in Johannesburg, and that the signal sequences are those used in that town. The installation in Oxford Street, London, is similar as far as the progressive phasing is concerned.

By setting the local timings correctly good progression

Disadvantages of Fixed-Time Progressive Systems

All the foregoing systems may be placed in the category of " fixed time " signals, as, apart from manual adjustments, the " go " and " stop " periods are predetermined and invariable. Frequent adjustment in the case of most systems is prohibitive on purely economic grounds, and in any case such adjustments can at best be only arbitrary. In other words, such systems exhibit many of the disadvantages of isolated fixed-time signals, as there is no self-adjustment with traffic variation. Traffic is held up when intersections are empty, and an additional drawback is that the arbitrary speed imposed by the progressive planning is suitable for only one particular traffic density, so that at all other densities the drivers find themselves continually being held up owing to the fact that they are driving either too fast or too slowly for the signals.

A chart showing typical journeys through the Oxford Street system is given in Fig. 24.

Fig. 22A.—General operation diagram of typical fixed-time progressive system.
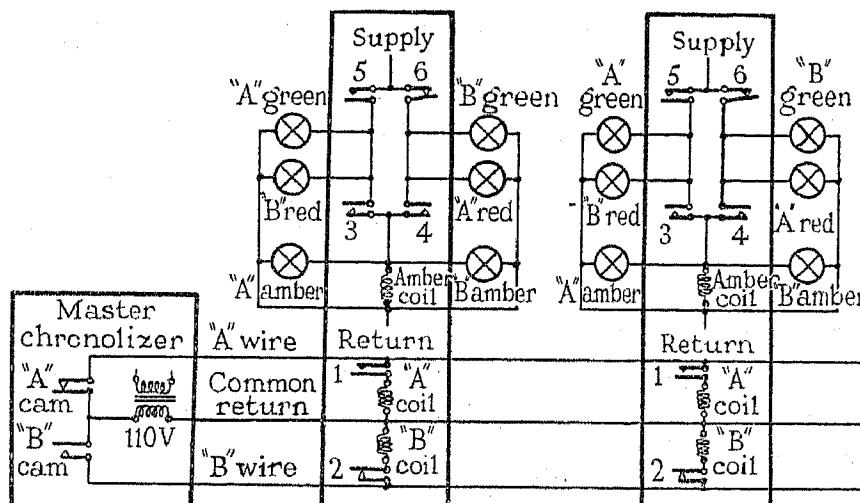
Fig. 22B.—Circuit principles of typical fixed-time progressive system.

can be obtained, but as the local settings are not altered when the cycle time is changed, the " go " and " stop " periods do not vary in proportion to the latter. Further, each change of right-of-way must take place within half of the shortest cycle-time on which the system is to operate; or, conversely, the minimum cycle-time must be more than twice as long as the longest time between tie-line reversal and transfer of right-of-way.

These effects can be seen clearly on comparing the time-and-distance diagrams for two different cycle-times (Fig. 23). Another interesting feature is that the " A " and " B " wire energization-periods when placed on the basic time-and-distance diagrams must take up positions of symmetry with the traffic bands, in order to avoid difficulties due to the impossibility of having two changes in any one half-cycle. The symmetry is no longer maintained when the cycle time is changed.

This system has been in operation in Oxford Street since July, 1931, and has given excellent service.

Combination of the Flexible-Progressive and Vehicle-Actuated Principles

The disadvantages of fixed-time progressive systems became more apparent in the light of the efficiency of vehicle-actuated controllers, and as a consequence efforts were made to obviate the weak points of the former by embodying the vehicle-actuated principle in flexible progressive systems. A map showing the principal installations of the types described is reproduced in Fig. 25.

BASIC REQUIREMENTS FOR VEHICLE-CONTROLLED PROGRESSIVE SYSTEMS

If reference is made to the hypothetical time-and-distance diagram shown in Fig. 21 it can be seen that there are certain fundamental conditions, as follows:—

(a) The right-of-way must be available for the main-road traffic at the various intersections at the times indicated, i.e. it must not be possible for right-of-way to

be withheld from the main-road traffic trains by side-road traffic.

(b) It must not be possible to take the right-of-way from the main road until the two trains in opposite directions have *both* arrived and established themselves.

(c) The side-road traffic must be afforded special preference during the periods marked as " red " if it is to be passed through at this most propitious time in the face of possible continuous main-road traffic.

PERFORMANCE OF THE LOCAL CONTROLLER

Consideration of these conditions led to the division of the local-controller cycle into preference periods, one for each phase, each initiated by a pulse from the master controller. Each preference period was subdivided into

of traffic in opposite directions, in order to prevent premature change of right-of-way to the opposing road with resultant obstruction to the second train.

" *Vehicle-actuated* " *period*.—Changes from one road to the other could take place under ordinary vehicle-actuated conditions, except that there was to be a " bias " for the road having preference.

" Prevent " and " privilege " periods are not necessary in the case of side roads unless the side roads are also progressively signalled. When not required they are abbreviated to a nominal value.

The local controllers may be either fully vehicle-actuated or semi-vehicle-actuated. The former naturally affords a maximum of vehicle actuation, but it is of course more expensive. Semi-vehicle-actuated systems,
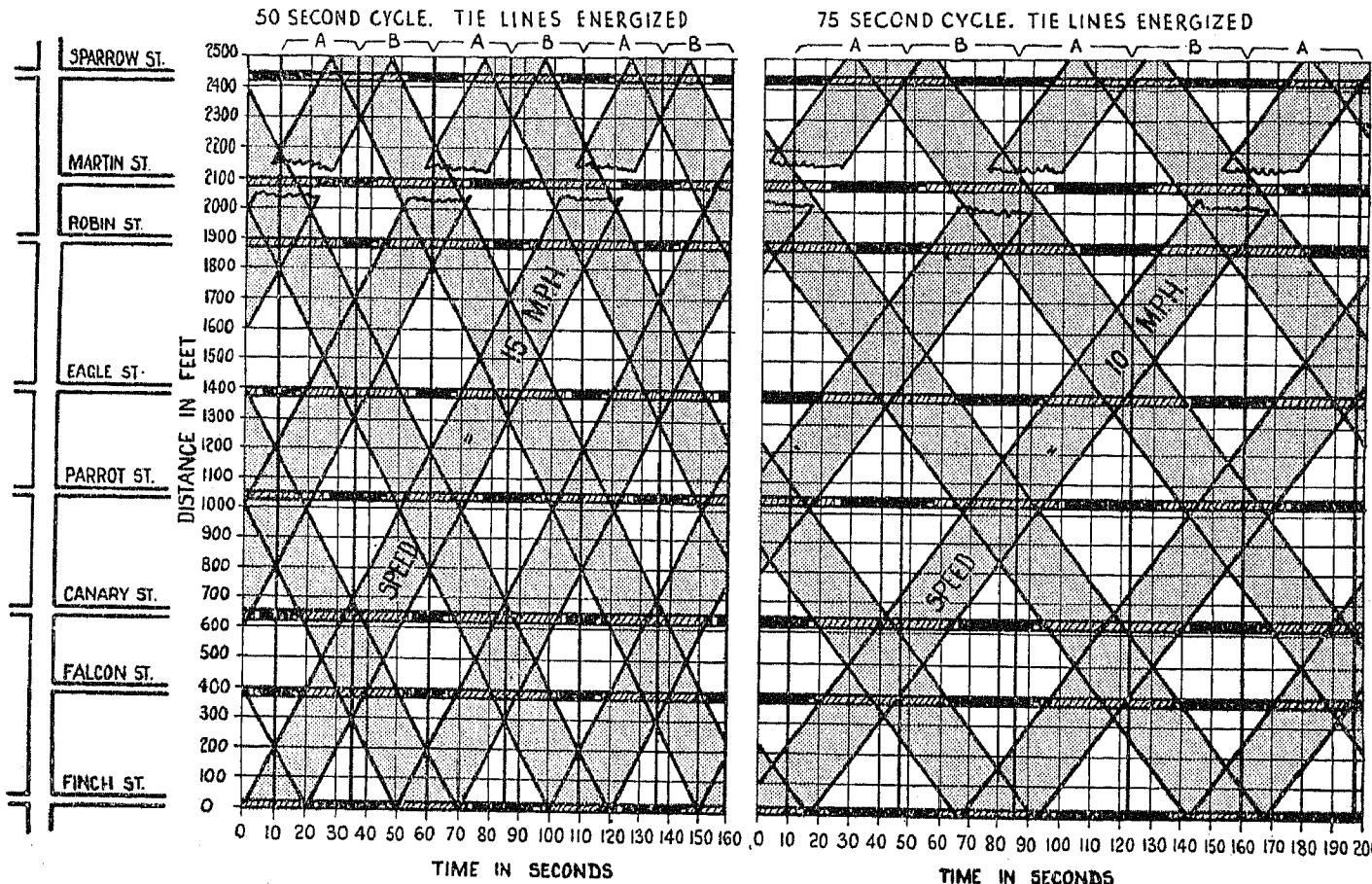

Fig. 23.—Hypothetical time-and-distance diagrams for typical fixed-time progressive system.

" prevent," " privilege," and " vehicle-actuated " periods, as shown in Fig. 26. The functions of these periods were as follows:—

" *Prevent* " *period*.—If the road which was losing preference had not taken the right-of-way by the commencement of this period, it was prevented from doing so until after the passage of the important trains of traffic which were due to arrive in a very few seconds, and was thus prevented from obstructing such trains.

If the road which was losing preference had already taken right-of-way it might retain it, if required, throughout the " prevent " period.

" *Privilege* " *period*.—The road having preference had the right of immediate response to its demands, and no change from this road was to be permitted. The " privilege " period was to be made sufficiently long to cover any gap which might occur between the two trains

with detectors in the side roads only, cause more delay to the side-road traffic than do fully vehicle-actuated systems, though when a traffic integrator is employed the fact that the cycle time is reduced when the traffic is light minimizes this delay.

For successful adherence to the progressive plan at all cycle-times the prevent and privilege periods must vary proportionately with the cycle time, and in all existing systems this has been achieved by suitable variation in the master-controller pulse-lengths, one pulse being transmitted for each preference period. This method is being abandoned in new systems, however, an improved method involving the transmission of one master pulse per local-controller sub-period being substituted (i.e. 6 or 9 master pulses per cycle in place of the previous 2 or 3 pulses per " cycle").

In the event of a pulse failure the controller changes
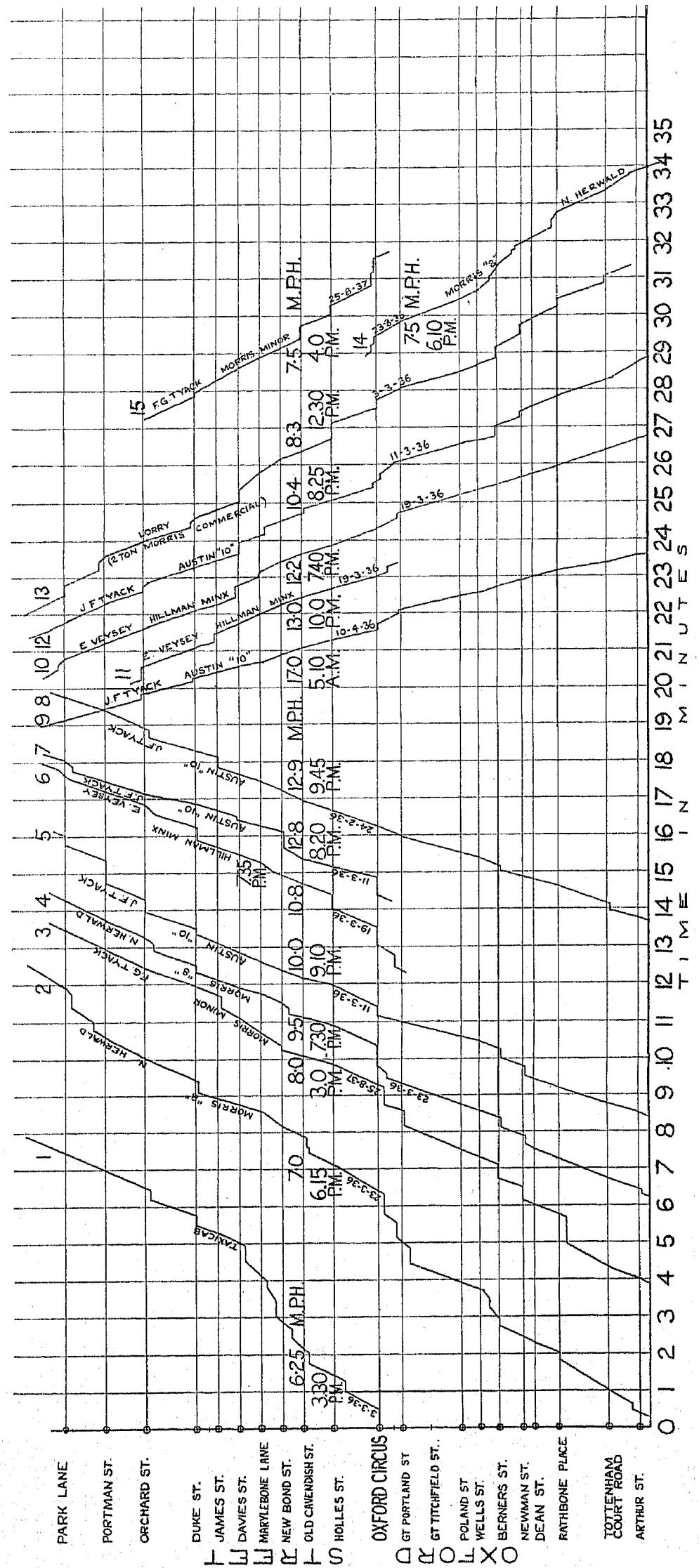
Fig. 24.—Typical journeys through Oxford Street system. (A fixed-time flexible progressive system.)
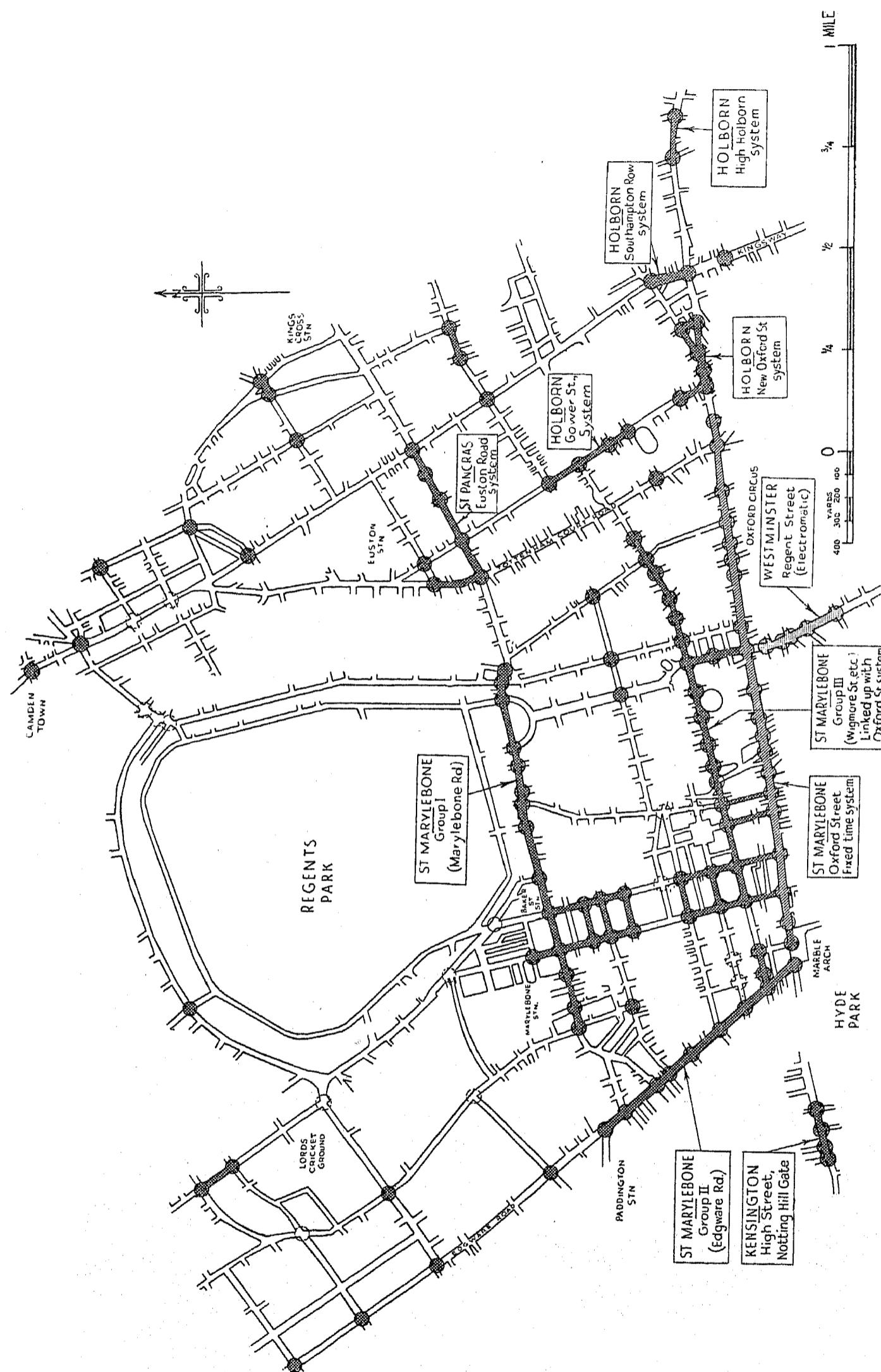
Fig. 25.—Map of principal signal systems of the types described in the West End of London.

over to isolated vehicle-actuated operation, and an alarm lamp glows on the side of the controller pillar.

The whole of the normal features of vehicle-actuated controllers, such as the inviolable "minimum green" period, speed timing, and amber extension and automatic reversion with arbitrary interruption, are present in the local controllers.

The maximum green timer, which in an isolated con-

THE MASTER CONTROLLER

The main functions of the master controller are to measure off the cycle time for the whole system, and to transmit co-ordinating signals to the various local controllers at appropriate parts of the cycle.

The master controller transmits pulses to initiate the preference periods (in the old system) or the progressive sub-periods (in the new system) in accordance with the
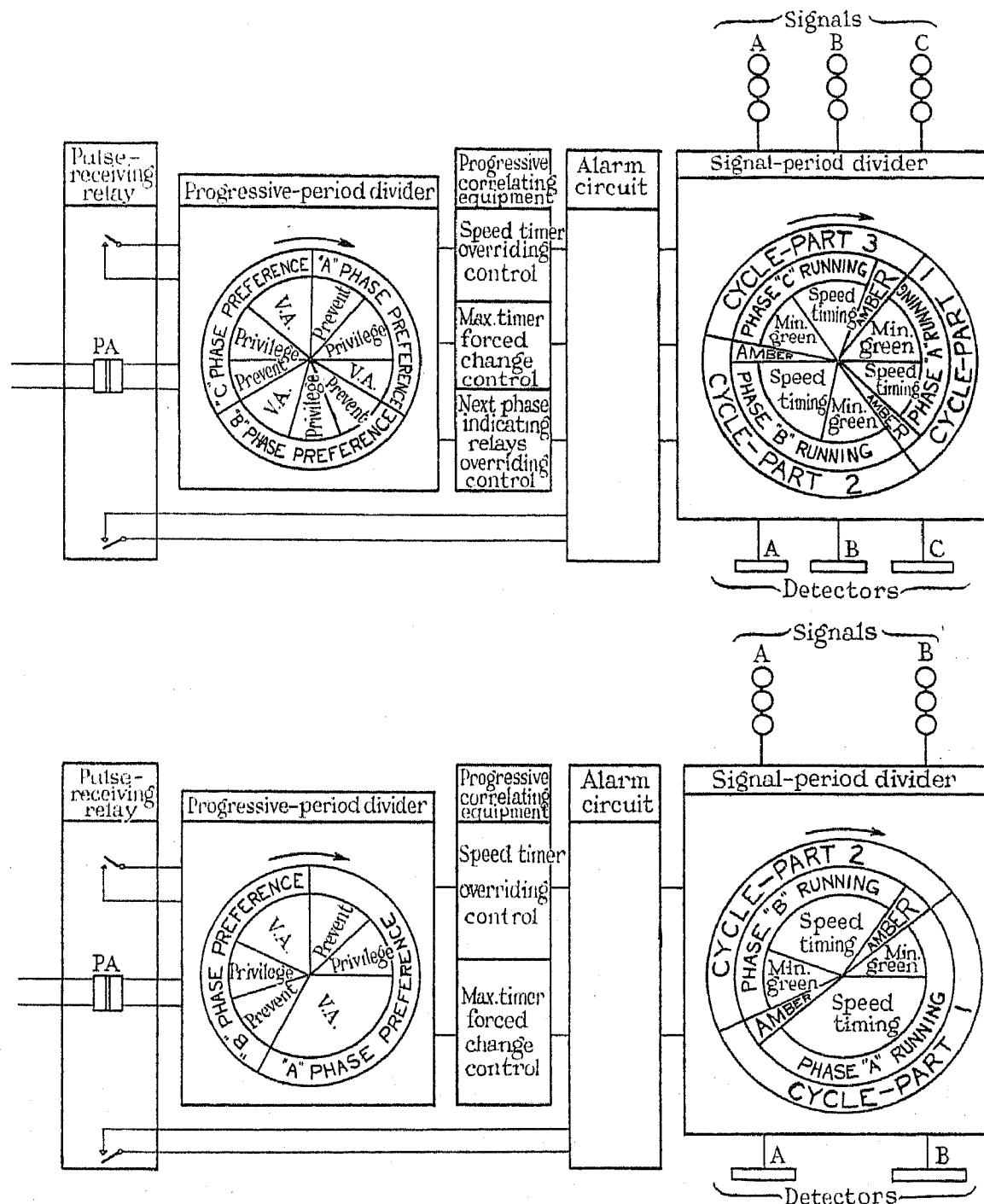

Fig. 26.—Main functions of local controllers in vehicle-actuated flexible progressive systems.

The alarm circuit cuts out all progressive control in the event of pulse failure. The "signal period divider" comprises the whole of the equipment which would be provided in an isolated controller. The progressive periods vary in proportion to the cycle time.

troller serves to determine the maximum waiting time in the face of continuous traffic, is not required to operate in its normal manner when the controller is working progressively, as the progressive control ensures that even under the worst conditions vehicles do not have to stop for longer than approximately three-quarters of the cycle time.

The local controllers are similar in construction to isolated controllers, but are equipped with additional relays and timing circuits.

relevant time-and-distance diagram. One pulse per cycle is reversed in polarity for phasing purposes. The cycle time may be varied between the limits of 30 and 120 sec. in small steps, and in the older systems the outgoing pulses vary in relation (but not in proportion) to the cycle time to effect appropriate proportionality of the prevent and privilege periods. The variation in cycle time may be made either manually or by means of a traffic integrator.

A " pulse setting field " comprising press-type keys or

a terminal panel is provided to enable the parts of the cycle at which the pulses are to be transmitted to be predetermined.

Master controllers are supplied in duplicate when required, and alarm circuits, which are fed from the power unit of the stand-by controller, are arranged to substitute one unit for the other in the event of any breakdown. When such a breakdown occurs alarm lamps glow to call attention to the fact, and in the case of the systems installed at St. Marylebone remote alarm indications are given in one of the local police stations and also in the Borough Council depot. A time switch is provided to switch from one unit to the other at regular intervals so as to keep both in good working order. It is also possible to change over manually.

The large master controllers in St. Marylebone comprise double-sided racks with two gates on one side, not unlike the line units in the early London automatic telephone exchanges. Pulse-setting keys are mounted on the two gates.

THE INTERLINKING CIRCUITS

The pulses transmitted from the master controllers are received at the local controller on a shunt-field relay, for the operation of which two wires are required. An individual pair is provided from the master to each local controller when Post Office lines are rented, or a single wire from the master to each local controller together with a common return in other cases. In addition there is a common pair, or a common single wire in conjunction with the above common return, for remote-control and telephone purposes. The principles are illustrated in Fig. 27.

The vertical commons are energized in turn through the cycle, so that by withdrawal of the appropriate key plungers or suitable cross-connections the horizontal commons can be energized at any particular parts of the cycle.

The pulse spacing and duration is determined by neon-tube timers. The positive pulses are obtained by discharge of an electrolytic condenser, while the negative pulses are obtained by straightforward connection of the 50-volt supply.

The shunt-field relay at the local controller is electrically polarized, and is arranged to receive negative pulses except in the case of the first pulse of the cycle, which is positive. By this means the controller is drawn into phase within 1 cycle of being switched on, and is maintained in phase.

In the older systems the " prevent " and " privilege " period durations are determined by charging two condensers simultaneously for the duration of the pulse, and then discharging them in sequence.

THE TRAFFIC INTEGRATOR
General

The principle of vehicle actuation has been applied to master controllers as well as to local controllers, and is used to operate an automatic adjusting device known as a " traffic integrator."

The purpose of the traffic integrator is to adjust the speed of the signal indications to suit the particular traffic density at the time. To do this a " key " intersection, at
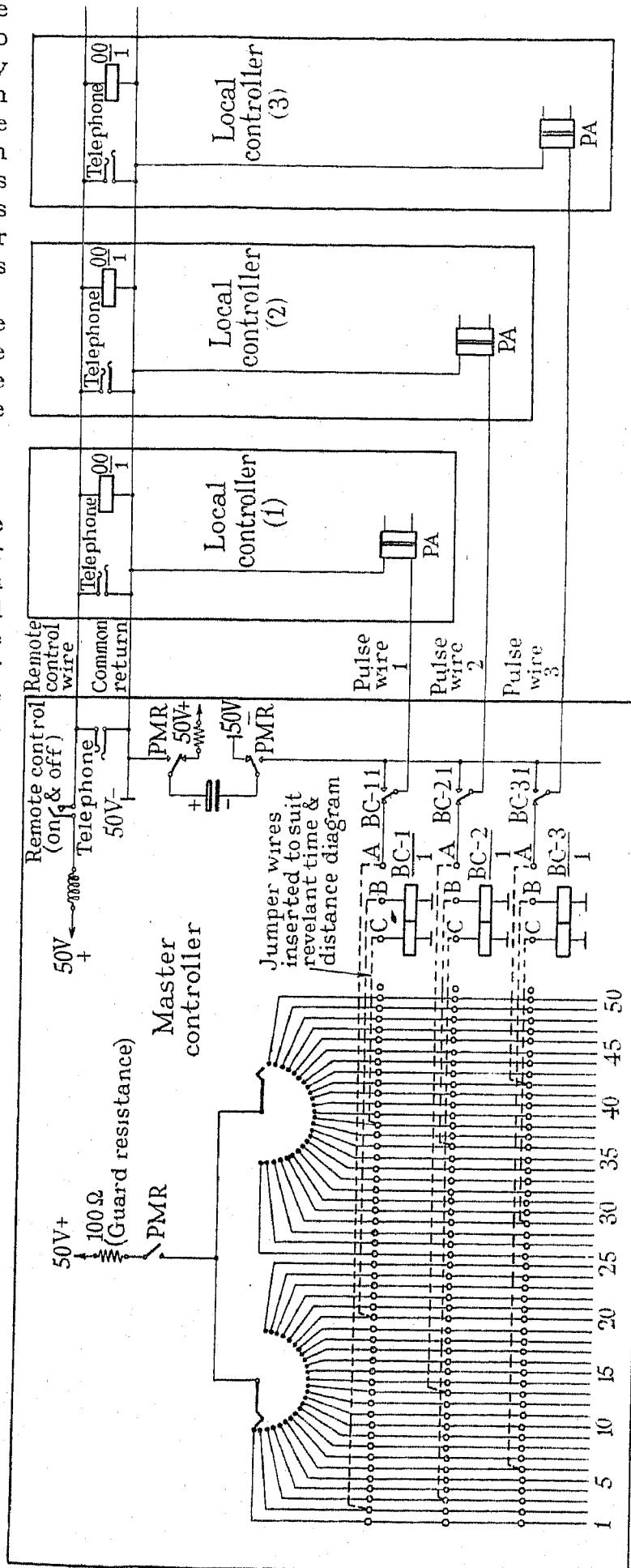

Fig. 27.—Progressive systems: typical pulse-transmission circuits.

which the traffic is representative of the whole system, is selected, and the ordinary local detector mats are utilized for the dual purposes of local signalling and traffic-counting.

The traffic integrator assesses the traffic volume over regular 5-minute periods and suitably adjusts the master-controller cycle time at the end of each period. The speed of the signals along the road is inversely proportional to the cycle time, and it follows that once the correct speeds have been determined for the various traffic-volumes and have been correctly associated with the various cycle-times the speed of the signals is always right for the vast majority of the traffic. In other words, the signals are arranged to follow the traffic, and there is no question of the drivers having to follow any arbitrary and probably unsuitable speed which is in any case unknown to them.

The natural speed of any particular volume of traffic depends on a large number of factors, such as the width
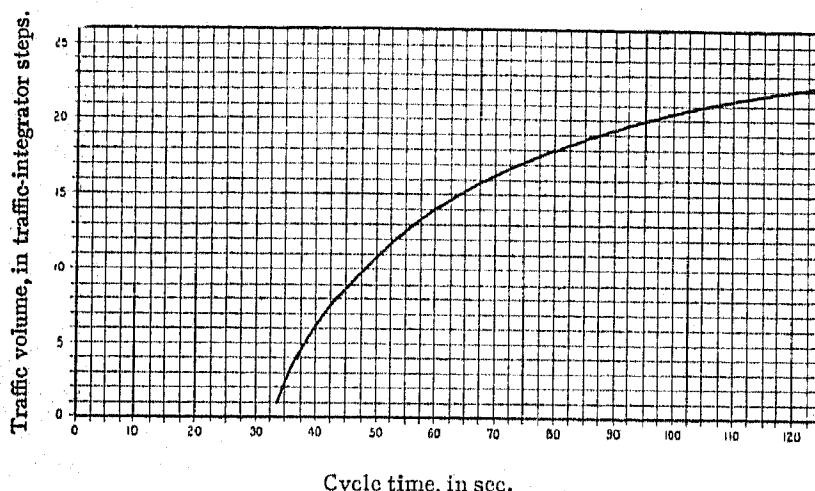

Fig. 28.—General relationship between traffic-volume and cycle-time (Adams's curve).

of the road, the gradient, and particularly the headway, and its determination forms a new study for which little information is yet available. Formulae for the relationship between traffic-volume and cycle-time have been produced by the Ministry of Transport, and these, together with practical experience, have formed the basis of the adjustments for the traffic integrator.

Fig. 28 gives a curve showing the general relationship of traffic-volume and cycle-time. This curve is based on Adams's formula, which is as follows:—

$$C = \frac{2a}{1 - 2\dfrac{T}{LS}}$$

where C = minimum practicable cycle-time, in seconds;
a = loss of time in starting up at each change-over, in seconds (this may be assumed to be approximately 16 sec., including an amber period);
T = total traffic at the intersection, in vehicles per hour;
L = total number of traffic lanes at the intersection;
and S = saturation traffic-density per lane (a lane is completely saturated when the traffic density is approximately 1 800 vehicles per hour).

The " traffic density " is the number of vehicles per hour divided by the number of lanes. The most efficient cycle-time is that at which the traffic in at least one direction is running to saturation density during each part of the cycle. This is also the minimum practicable cycle-time.

This and other formulae which have been proposed can be included under the general formula

$$C = \frac{a}{1 - kT}$$

where a and k are arbitrary constants.

These formulae have been based mainly on isolated intersections and, although they apply to certain parts of progressive systems, it may be found when the new systems have been sufficiently studied in practice that a modified form is more suitable. This applies particularly to the value assigned to a, which may be much reduced if, as actually happens, the majority of traffic is passed through a large system with very few stops.

It should be observed that the relationship between speed and cycle-time is not a definite quantity, but is determined by the design of the time-and-distance diagram. For any particular diagram, of course, the speed varies in inverse proportion to the cycle-time. It follows, therefore, that the time-and-distance diagram should be constructed for the maximum permissible speed with minimum traffic and the shortest practicable cycle-time.

A number of different cycle-times are available, and from these 22 have to be selected as the most useful for the particular case under consideration. A cross-connecting field is provided to enable any desired arrangement to be used.

It is desired that the integrator should follow what might be known as the " tidal ebb and flow " of the traffic, and that it should not impress on the system the moment-to-moment fluctuations which occur just at the key intersection. Five minutes has been selected as a sufficient period to smooth out the ripples, while at the same time permitting as many as 12 adjustments in an hour. The 5-minute readings themselves do not precisely follow the tidal ebb and flow, but may be either above or below the general level. It is therefore not desirable for the cycle-time adjustment to follow them exactly. If the difference between two 5-minute readings does not exceed 5 % the change is not regarded as significant, and no change is made in the cycle time. If, however, the difference exceeds this amount the cycle time is readjusted.

If we had no other knowledge about the tide level than a single 5-minute reading, we should regard it as equally likely that the observed value was above as that it was below the tide value, and we should set the cycle time to the corresponding value. In general, however, we know that the existing cycle-time has been fixed as the result of previous observations. If the new observed value is above the existing setting by more than the standard difference, it is reasonable, in view of our previous knowledge, to set the cycle time to a value intermediate between the existing setting and that demanded by the 5-minute reading. The new setting should, however, be within the standard difference from the observed value. The setting switch is therefore arranged so that, when it

moves to take up a new position, it stops short of the cycle time indicated by the traffic count, by an amount equal to the standard difference.

Traffic integrators are in use in the large progressive systems in Marylebone Road and Edgware Road in the Borough of St. Marylebone, and in Gower Street in the Borough of Holborn, and are at present being installed in Exeter and in Cape Town.

The Traffic-Integrator Circuit

The traffic integrator comprises the following circuit elements:—

(a) A timer circuit, to measure off the 5-minute periods. This is built up of a neon tube and condenser timer arranged to measure off 60-sec. periods, and a relay counter circuit.

(b) A counter circuit, to assess the traffic volume during each 5-minute period. This contains impulse standardizing relays to eliminate the effect of speed, a neon tube and condenser counter, and a uniselector for use as a " bulk " counter. The uniselector takes one step each time the condenser becomes fully charged as a result of the passage of a predetermined number of vehicles.

(c) A setting uniselector and complete set of timing resistances, to control the main neon-tube circuits of the master controller. This switch takes up the position indicated by the counter switch at the end of each 5-minute period, with the reservation regarding standard differences previously explained.

(d) A duplicate setting switch, to take over control while the main setting switch is rotating.

LINKING-UP OF IMPORTANT PROGRESSIVE SCHEMES

There are now three important and distinct progressive systems of signals converging on Oxford Circus, as follows:—

Oxford Street.—Chronolizer system (fixed time).

Regent Street (south of Oxford Circus).—Electromatic system.

Regent Street (north of Oxford Circus), Wigmore Street, etc.—Autoflex system.

The relationship of these systems is shown clearly in Fig. 25.

To ensure satisfactory traffic flow from one system to another, special junction arrangements have been made between the Oxford Street and Wigmore Street systems, and the cycle time is the same throughout the whole area. Control of the cycle time has been centralized in the new master controller.

The outgoing junction equipment from the new master to the original master at Oxford Circus comprises repeating relays which energize the Chronolizer " A " and " B " wires alternately for 12 and 13 Autoflex pulses. The original Oxford Street master is thus superseded but is left connected in such a manner that it can automatically take over the control again in the event of any breakdown in the new master controller.

Owing to the limitations of the early fixed-time system in Oxford Street it is not practicable to use an integrator in this case. The cycle time is set by means of a telephone dial located in a kiosk at Oxford Circus, the dialled

impulses being received on uniselectors in the Autoflex master controller at Margaret Street. The digits dialled represent the actual cycle-time. Thus, for a 65-sec. cycle, 6–5 is dialled.

A further difficulty that had to be overcome was that while the systems were both based on satisfactory time-and-distance diagrams at one particular cycle-time (50 sec.) they would no longer be in correct relationship if the cycle time was changed, owing to the fact that the increments were not proportional to the cycle time and were not symmetrical in the Oxford Street system (cf. Figs. 21 and 23). It has been necessary to effect a compromise, and the correction factor which has been found most suitable is a delay of 14 sec. from the Chronolizer datum line to the Autoflex datum line.

MULTI-PHASE LOCAL CONTROLLERS

Multi-phase controllers present special difficulties when used in progressive systems, as they fundamentally require cycle-times longer than those for 2-phase controllers. In addition it is sometimes necessary to control the roads to which right-of-way may be transferred even during the vehicle-actuated periods. When the latter is the case, transference is only permitted to the next road to have preference; so that in effect the cycle parts occur in the correct order and at the correct progressive times, but the durations of the periods are flexible. The difficulty regarding cycle time does not arise if the whole or the majority of the controllers are of the same multi-phase type, and it is of interest to note that progressive schemes built up of 3-phase controllers are at present being installed in Exeter and Cape Town.

An additional feature of one of the Exeter schemes is that the controllers convert automatically from 3-phase to 2-phase working and vice versa, to suit heavy and light traffic conditions respectively. The master controller, which includes a traffic integrator, is being arranged to operate on two distinct time-and-distance diagrams and two distinct integrator curves.

ADJUSTMENT AND TESTING

Too much emphasis cannot be laid upon the necessity for careful planning to determine the adjustments required to meet the traffic conditions, and for thorough testing under working conditions. However efficient the controllers may be, mechanically and electrically, they cannot play their part fully unless the progressive planning is suitable for the traffic with which the system has to deal. In a well-planned system, the traffic is passed through without unnecessary delay, and the general effect is that the streets appear emptier than before the signals were brought into use.

The methods adopted by the St. Marylebone Borough Council were particularly thorough, and the results have justified the efforts expended. The methods may be summarized as follows: (1) A traffic census. (2) Time-and-distance diagram planned, and times tabulated. (3) Local controllers operated as isolated controllers, one at a time, over periods sufficiently long to enable the optimum adjustments to be determined. (4) Local controllers operated on a fixed-time progressive basis, commencing with very small groups, and working on one cycle-time only. (5) Switch over to vehicle-actuated
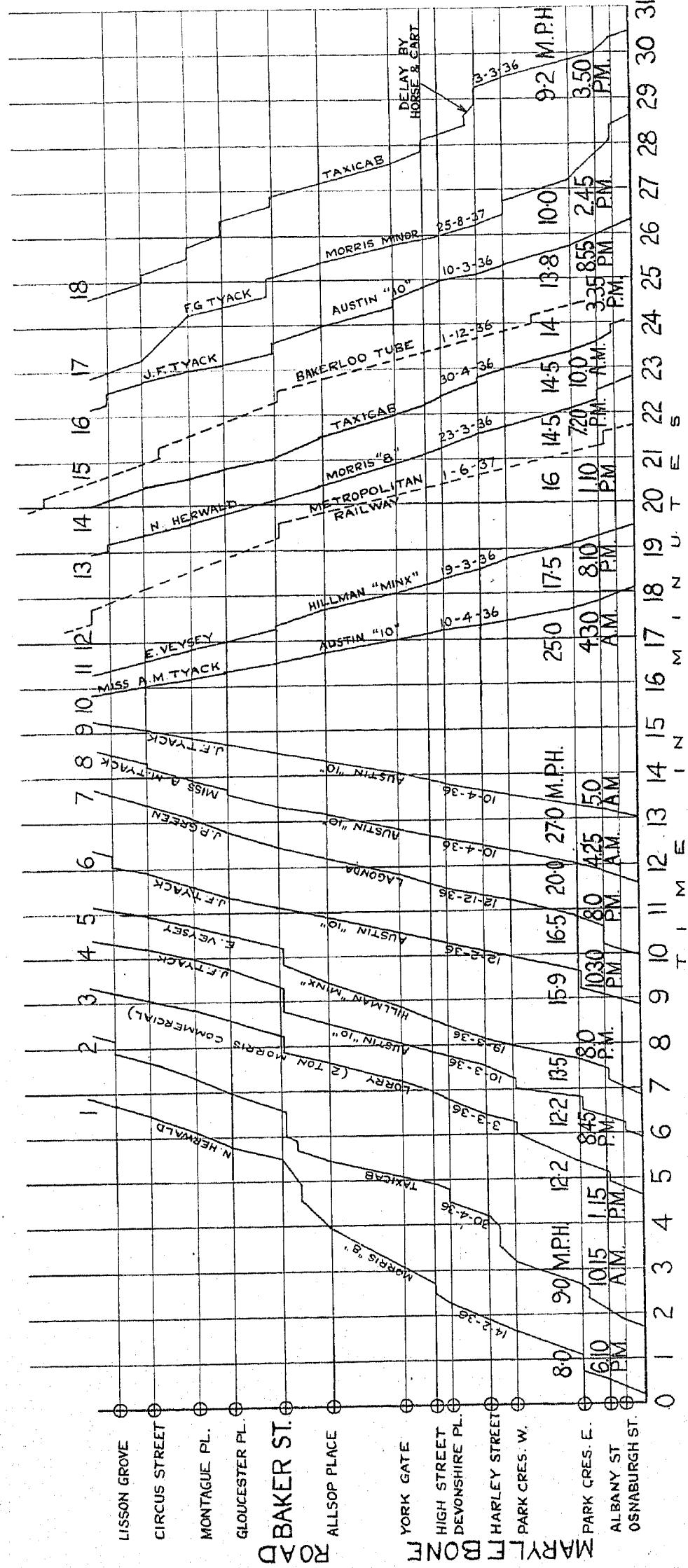
Fig. 29A.—Main-road journeys through Marylebone Road system. (A semi-vehicle-actuated flexible progressive system, with traffic-integrator control.)

working, still keeping to one cycle-time only. (6) Switch in the traffic integrator. (7) Drive through and through the system a large number of times in all directions.

Unnecessary congestion can be eliminated by thorough testing and careful readjustment as the tests proceed.

turning vehicles in particular may delay following vehicles so that these get out of their progressive train and are perhaps stopped at several intersections. The proof of satisfactory operation is the removal of the congestion or danger which existed before the system was applied.
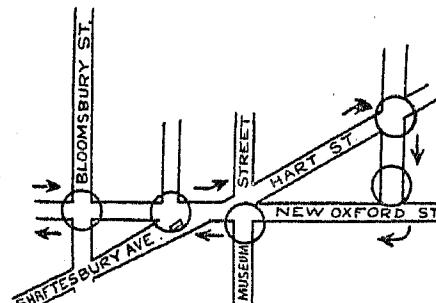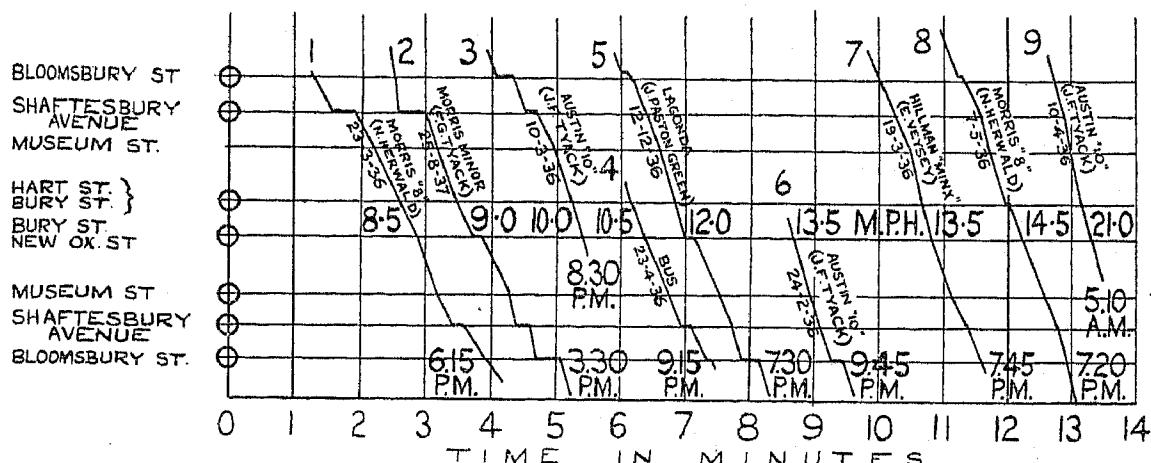

Fig. 29B.—Main-road journeys through New Oxford Street system. (A fully vehicle-actuated flexible progressive system, without a traffic integrator.)

PERFORMANCE OF PROGRESSIVE SYSTEMS

Traffic engineers have been seeking some reliable method by which to gauge the efficiency of progressive systems in their various forms, and have found that it is extremely difficult to produce such a method. Firstly, no two control schemes can fairly be compared unless they deal with exactly the same amount of traffic on identical road layouts. Secondly, the delay figures produced may at first sight appear to militate against one section of the traffic in the new system. It is probable in such cases that the facilities given to pedestrian or some other traffic which previously had difficulty in crossing a dense traffic stream, have been improved out of all proportion, with resultant reduction in what is known as " the toll of

Numerical results have been obtained, and as an example the figures for the intersection of Marylebone Road and Park Crescent East can be quoted. Park Crescent East is a continuation of North Regent Street and is a coach route. There is no near control, either north or south, so that the side-road traffic arrives at random. In addition, this intersection, although third from one end of the main system, is eleventh from the other end, and it is to be expected that the vehicles are becoming more widely spaced here than when they were first marshalled. An examination was made at about 7.30 p.m., when the traffic flow was 1 740 vehicles per hour (v.p.h.). The main-road figure was 1 098 v.p.h. and the side-road 642 v.p.h. Of the main-road traffic, 78·2%
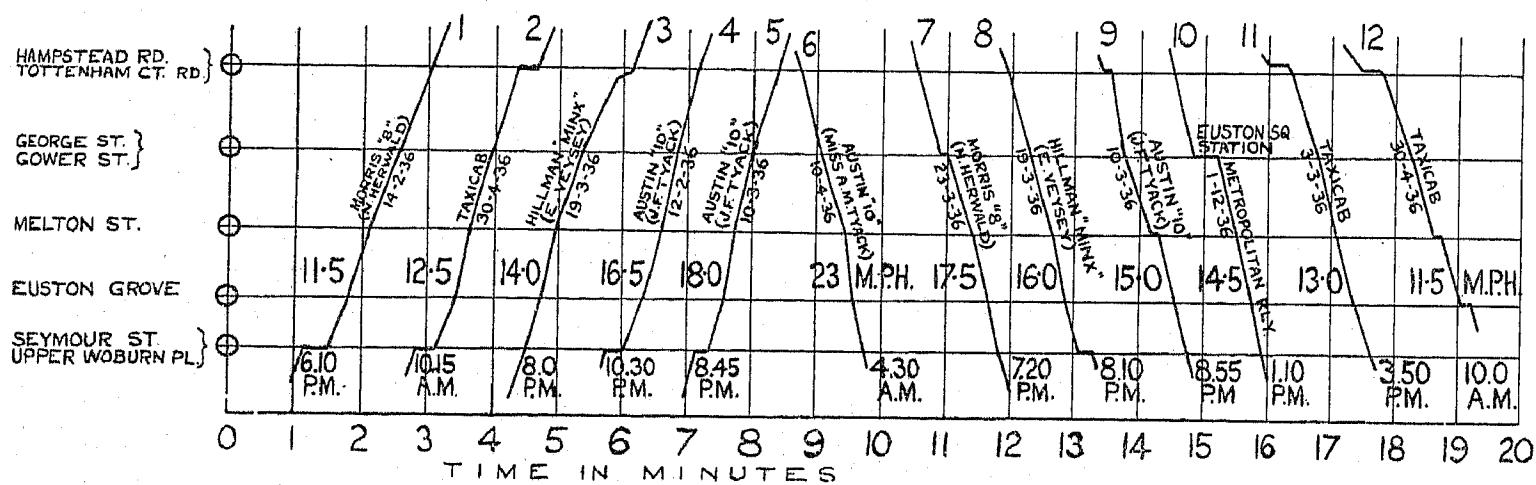

Fig. 29c.—Main-road journeys through Euston Road system. (A fully vehicle-actuated flexible progressive system, without a traffic integrator.)

the road." Miracles must not be expected, and it must be remembered that a train of road traffic comprising a number of independent vehicles does not behave exactly like a railway train with all the vehicles coupled. Even though the traffic integrator adjusts the speed to suit the majority of the traffic some drivers will go too fast and others too slowly, while vehicles drop out of or join the main-road traffic at every intersection. Right-hand-

was not stopped at all. The average delay for all the main-road traffic was 2·3 sec. Of the side-road traffic, 65 % was stopped. As the main-road traffic formed exactly 65 % of the whole, and as the side-road traffic was arriving at random, this result cannot be regarded as other than satisfactory.

Perhaps the most conclusive method of testing is by driving through the system under a variety of conditions;
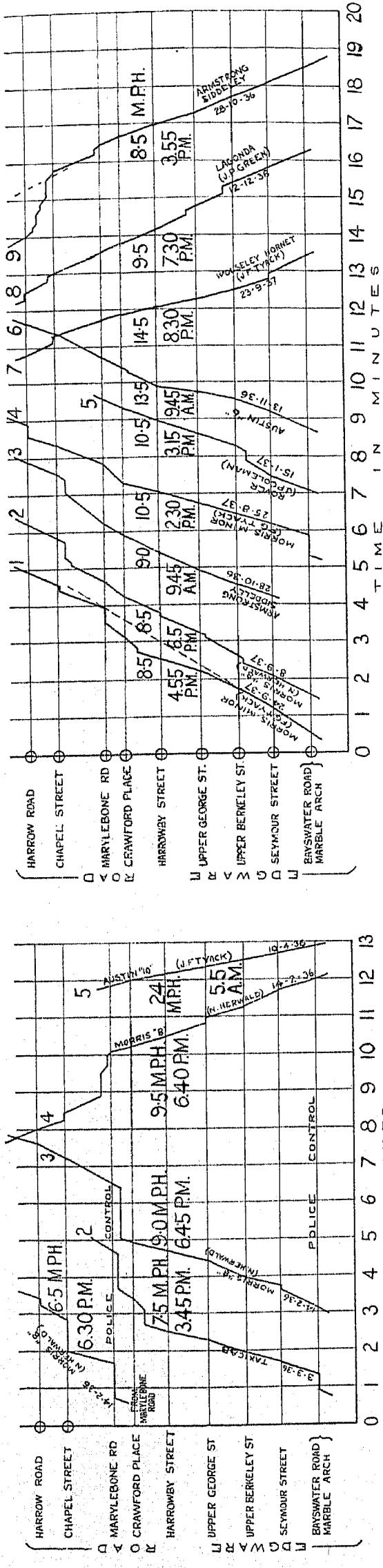
Fig. 29D.—Main-road journeys through Edgware Road system. (A semi-vehicle-actuated flexible progressive system, with traffic-integrator control.)

Fig. 29E.—Side-road journeys across fully vehicle-actuated flexible progressive systems; also journeys through Gower Street system, with traffic-integrator control.
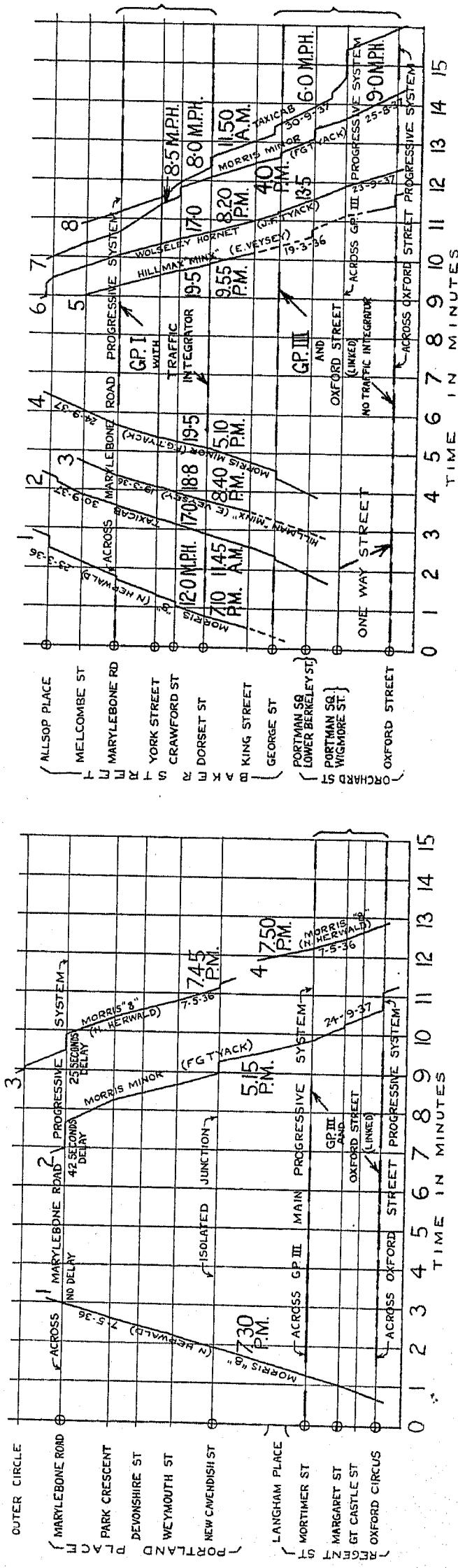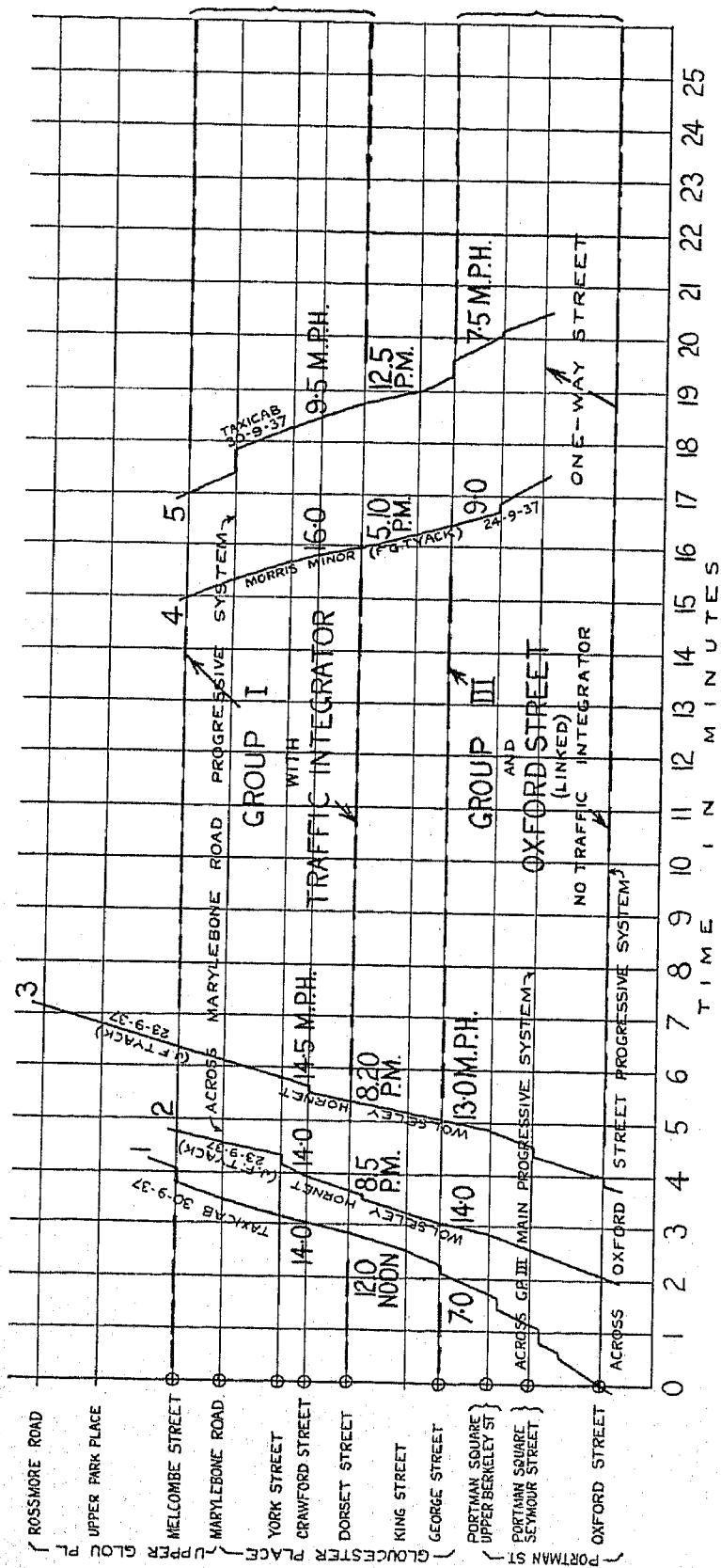
Fig. 29F.—Side-road journeys in semi-vehicle-actuated flexible progressive systems (with and without traffic-integrator control); also side-road journeys across Oxford Street fixed-time progressive system.

charts showing runs through various vehicle-actuated flexible progressive systems, but without traffic integrators, are reproduced in Figs. 29A to 29F. In Marylebone Road (Fig. 29A) it is now possible to drive along a mile of main road at the general traffic speed without a stop or with only one stop, unless obstructed by slow-moving or right-turning vehicles. During the busy hour, when the traffic flow at Marylebone Circus is as high as 3 600 vehicles per hour, the progressive speed is about 12 m.p.h., while at slack times it is considerably higher.

No long representative fully vehicle-actuated system exists for comparison with the long semi-vehicle-actuated systems. The greatest number of intersections which can normally be traversed in a single journey is 5, this occurring in the New Oxford Street and Euston Road systems. The New Oxford Street system, however, includes certain one-way streets which are interconnected by a spur taking both " up " and " down " traffic in the same direction, and the author has found that by using this one-way spur and returning along the street which comprised the commencement of the run it is possible to obtain a progressive journey through seven intersections. These are shown in Fig. 29B. This journey includes two right-angle turns.

It may be asked whether the main-road efficiency is obtained at the expense of the side-road traffic. The side-road traffic is passed through after a delay varying from zero up to a maximum of approximately three-quarters of the cycle time, the average delay in the case of a 60-sec. cycle being 10 sec. for a semi-vehicle-actuated system and 2·5 sec. with full detection, assuming random traffic. In general, however, these delays are justifiable, as in the daytime there is a great probability of the presence of main-road traffic *during the main-road preference period* and the delays would probably be considerably longer without any control at all. The delays are most noticeable during times of light traffic, but it is preferable to subordinate the interests of the minority of night traffic to the overwhelming majority of the day traffic. Examples of side-road journeys crossing various Autoflex progressive systems are shown in Fig. 29E and 29F. Another important fact is that full progressive facilities are available for the side roads as well as the main roads, and in such cases the delays may be regarded merely as the time taken to get into step with the progressive plan. To illustrate this fact more clearly it may be mentioned that in St. Marylebone, Group I, true progressive traffic flow with traffic-integrator control obtains not only along Marylebone Road but also along Baker Street, Gloucester Place, York Street, Crawford Street, and Dorset Street (see Fig. 25).

CONCLUSION

It will no doubt have been realized from the descriptions and illustrations that modern street traffic-signal equipment bears a remarkable similarity to telephone-exchange equipment, and it has once again been established that where complex electrical switching is required telephone apparatus with its ready adaptability forms an ideal solution. Apart from the contribution of the telephone industry, however, which applies principally to the controllers, many other branches of the electrical industry, such as electric supply, lamps, cables, rectifiers, and rotating machines, are represented in traffic signalling equipment.

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DISCUSSION BEFORE THE INSTITUTION, 4TH NOVEMBER, 1937

Mr. A. E. N. Taylor: It must come as a surprise to many of us to see that the idea of traffic control by automatic means was thought of 70 years ago. I have a photographic reproduction of the original police notice, and it is interesting to note that even in those days they realized that it was unwise to tell drivers of vehicles, and people in charge of horses, that the " go " signal meant other than " Proceed with caution." It would also appear from the notice that our ideas on the control of pedestrians at crossings are by no means new, for with regard to the " Stop " signal—two semaphore arms displayed horizontally—it is stated that this would be displayed only when it was necessary that vehicles and horses should actually be stopped on each side of the crossings to allow passengers to cross on foot. As the author points out, unfortunately the experiment was terminated by the explosion of the signal. It may be thought that it was premature, in that the right forms of illuminant and power were not available, but it is of interest to note that the first vehicle-actuated signal to be erected in this country also exploded, not as a result of a defect in the equipment but owing to an accumulation of sewer gas.

On page 125 the statement is made that " The first attempts at vehicular control of ordinary traffic signals took place in the U.S.A." I would add that in this country in 1926 or 1927 an attempt at vehicle-actuated control was made at Canterbury. The equipment was purely mechanical in operation, and, as in the case of the original police signal, defects were apparent and it was never brought into proper use.

On page 126 the author says: " One other modern type of signal deserving attention is the portable type used during road works in and around London." I think that I should draw attention to the fact that the Minister of Transport has authorized the ordinary conventional 3-light signal for that purpose, and also a 2-light signal, showing red and green only, and they are in use in the provinces. I disagree with the statement on the same page in which the author, referring to the suspended type of signal used over the centres of intersections, gives as one of its disadvantages its high initial cost. When one compares the suspended type of signal with the conventional British layout shown in Fig. 1, it seems clear that the former does not require so much equipment, and, provided tram poles or similar poles are available, the equipment should be cheaper. The list of basic requirements for vehicle-controlled progressive systems given on pages 141 and 142 is by no means complete. On page 141 some limitations are given of the settings of a typical fixed-time system. I think it should be made clear that these are limitations of the system to which the author refers, and not general limitations of the fixed-time system.

In conclusion, I would support the statement, made on page 150, that traffic engineers have found it difficult to produce a " reliable method by which to gauge the efficiency of progressive systems in their various forms." If any members of The Institution feel disposed to consider the matter, we at the Ministry of Transport and, I am sure, the manufacturers also, shall be very pleased indeed.

Mr. T. P. Preist: I agree with the author on the need for standardization of the descriptive terms used in traffic-signal engineering; I think that this is long overdue, and possibly a small committee might be set up to deal with the matter.

In describing the detector, the author states that the top of the mat projects slightly above the road level to present a good striking face. Apart from possible discomfort to road users due to this projection, is not there some danger of increasing the road wear on the remote

side of the detector? He also states that " In order to prevent damage by the large volumes of air displaced by heavy vehicles, and to permit self-adjustment to the varying atmospheric conditions, air leaks are provided in the system by means of felt washers." I assume that the bellows are sufficiently robust to stand the maximum pressure which could be attained without the leaks, because, since the leak has some resistance, it seems to me that the maximum pressure must be attained, if only instantaneously.

The author also remarks that the all-relay controller provides a ready solution to the " first come, first served " problem, but I should like to point out that this is just as readily solved by electromechanical and relay methods. One method uses a rotating camshaft.

It is a matter of some controversy whether the " first come, first served " method of operation is ever truly justified, and the paper gives a number of limitations of such a system. The author refers to a difficulty which occurs with the fixed-rotation system of signalling, associated with the second choice away from the main traffic phase. He also refers to a condition which arises with the " first come, first served " method, in which one phase may receive right-of-way twice before a waiting call is dealt with. I imagine that of these two the second is the more irritating to a waiting driver, and it seems to me to be a point in favour of fixed rotation.

There seems to be, as the author suggests, a tendency on the part of local authorities to signal the more complex junctions, because of the flexibility of signals; but, to ensure the greatest efficiency of signalization, nearby junctions, no matter how simple, should also be signalled and suitably interlinked with the main intersection.

The author observes that with the flexible progressive system the speed of the traffic is inversely proportional to the cycle time. When the traffic increases, the natural tendency is for it to flow at lower speeds, but it has always seemed to me doubtful whether the natural lower speed and the arbitrary lower speed obtained by increasing the cycle time are the same. Should not the system be re-planned for the best speed with each change of cycle time? There are practical drawbacks to this suggestion but it is a point of considerable interest.

Finally, with respect to multi-phase controllers, the author may be interested to know that 4-phase units are already in operation in the City of London at Blackfriars Bridge, and will shortly be brought into operation at Piccadilly Circus. Both installations operate on the flexible progressive system.

Mr. B. O. Anson: It is interesting to those of us who are telecommunication engineers to see the great influence which our art is exerting on everything which may be regarded as involving problems of discrimination. Often those who have to solve such problems make mistakes owing to the fact that they overlook the automatic telegraph and telephone development in trying to do so. One case which stands out is that of the totalisator: in the first instance, the solution of the problem there involved was sought on the basis of using electric motors; this attempt failed, and those responsible had to fall back on the devices which had been standardized for automatic telephony. Similarly with the remote control of power: a variety of devices were tried before the utilization was

adopted of devices standardized in telephony. The designers of traffic control systems in this country had a great advantage in that they were originally telephone engineers. They have always given a great deal of prominence to the devices which have been standardized for telephony.

The diagrams in this paper are presented precisely as a telephone engineer would present them, and anyone trained as a telephone engineer can at once see exactly how the circuits work. Much of the apparatus consists of components which have been standardized for telephone purposes. I am interested to see that Type 3 000 P.O. relay constitutes the bulk of the apparatus shown by the author; and the reliability with which it works was emphasized by the ease with which, in his demonstration, he changed over from one set of about 40 relays to another similar set without any delay or misadventure.

It appears that standardization has to go much further than the standardization of components. Those concerned with traffic control should benefit by the experience of the Post Office, who found it necessary to have a scheme whereby the contracts placed with the manufacturers are based on absolutely rigid specifications. Similarly, to effect this an effort must be made to introduce a standardized system of traffic control.

Another region where Post Office experience might help the traffic-control engineers is " maintenance." Standardization has a bearing on maintenance. While the ownership of traffic-control devices is in the hands of the various municipalities and towns, and in some big cities is distributed over a number of bodies, it must be difficult to secure adequate maintenance. I should have thought the time had arrived when the maintenance of all traffic-control apparatus throughout the country should be put under some body like the Ministry of Transport itself, who could exchange views with the Post Office, using identical apparatus, so that similar practices would be adopted on both sides. It would be interesting if subsequent speakers who are connected with the Ministry could give us any information on this subject.

Another point which arises in connection with maintenance is the complexity of this type of apparatus. It is necessary to put a stop to the continual adding of functions, because otherwise in the end the apparatus will become so complex that it will be subject to excessive maintenance difficulties.

Mr. W. F. Adams: I happen to be able to compare the test runs recorded in this paper with some runs which were made in August, 1935, prior to the institution of signal control (see Table A). It is necessary to bear in mind that the conditions for these test runs may have been different from those of the author, as they were taken at different times of the year. The basis of comparison adopted is to select from the two sets of results those which were taken at similar times of the day, and to exclude comparisons based on the result of a single test run only.

It will be noticed that the Edgware Road northbound traffic has been speeded up from an average of 9·8 to an average of 10·4 m.p.h., but the Marylebone Road eastbound traffic seems to be rather worse off under signal control, having been slowed down from 13·4 to 11·2 m.p.h. In the latter case, however, instead of 5 junctions

which were police-controlled there are now 14 which are signal-controlled. In the interests of safety and the general regularization of traffic each motorist travelling along that road is subjected to a loss of 10 sec.—not a great sacrifice in that cause. In the case of Baker Street northbound traffic the speed has improved from 15·8 to

Table A

Route and direction of traffic	Time of day	Speed, in m.p.h., found by:—	
		W. F. Adams	The author
Edgware Road, north-bound	9.45 a.m.		9·0
	9.45 a.m.		13·5
	11.10 a.m.	11·0	
	11.20 a.m.	10·9	
	2.30 p.m.		10·5
	2.55 p.m.	9·7	
	3.10 p.m.	7·6	
	3.15 p.m.		10·5
	4.55 p.m.		8·5
	Average speed	9·8	10·4
Marylebone Road, east-bound	10.0 a.m.		14·5
	11.30 a.m.	14·3	
	11.50 a.m.	11·7	
	2.45 p.m.		10·0
	3.20 p.m.	14·0	
	3.35 p.m.	13·5	
	3.50 p.m.		9·2
	Average speed	13·4	11·2
Baker Street, south-bound (Marylebone Road to George Street)	11.50 a.m.		8·0
	12 noon	8·2	
	12.15 p.m.	12·3	
	3.43 p.m.	17·1	
	4.0 p.m.	14·9	
	4.0 p.m.		8·5
	Average speed	13·1	8·25
Baker Street, north-bound (George Street to Marylebone Road)	11.45 a.m.		17·0
	12.10 p.m.	20·9	
	12.25 p.m.	15·3	
	3.50 p.m.	12·9	
	4.10 p.m.	13·9	
	5.10 p.m.		19·5
	Average speed	15·8	18·25

18·25 m.p.h., but in the case of Baker Street southbound traffic the runs prior to signal control show an average speed of 13·1 m.p.h. compared with the author's 8·25 m.p.h., a very substantial difference for which I have not been able to account.

Table B compares the delay figures given for the Marylebone Road–Park Crescent East junction with some figures taken in September, 1935, under police control.

In spite of the increase in cross traffic from 438 to 642 v.p.h., the average delay to each main-road vehicle has been reduced from 6·1 to 2·3 sec.—to one-third, roughly speaking—which is very remarkable; and the proportion of main-road traffic which is not stopped has gone up from 72 to 78 %.

Fig. 17 contains a good deal more information than is apparent on the surface. For instance, no reference is made to the traffic volume, but a study of the diagram shows that the traffic on cycle-part 2, Phase B, was in the region of 160 v.p.h., on Phase D the traffic was approximately 120 v.p.h., and the number of calls per hour made by pedestrians was in the neighbourhood of 90. From Fig. 17 it can be seen that each phase was omitted a certain number of times; cycle-part 2, Phase B, for

Table B

	Values found by:—	
	W. F. Adams	The author
Time of observations	2.30 p.m.	7.30 p.m.
Total traffic (v.p.h.)	1 926	1 740
Traffic on main road (v.p.h.) ..	1 488	1 098
Traffic on minor road (v.p.h.)..	438	642
Percentage of main-road traffic not stopped	72	78
Average delay to each main-road vehicle	6·1 sec.	2·3 sec.
Percentage of main-road traffic to total	77·3	65
Percentage of minor-road traffic stopped	60·2	65

example, was omitted 4 times. It will be understood that the more traffic there is on a phase the less frequently will that phase be omitted. It is possible to put this statement in mathematical form, and by probability methods to find out what traffic volume is implied. The probability of cycle-part 2 being omitted is approximately 4/80 (= 0·05). This occurs in the cycles in which no call is received on Phase B. Using the notation of Reference (2) in the Bibliography,

$$P(O) = e^{-m} = 0·05, \text{ as above}$$

where m is the mean number of vehicles arriving on the phase during one cycle and e is the base of natural logarithms. Solving this equation, $m = 3·0$. In $1\frac{1}{2}$ hours recorded, there were 80 cycles; hence the traffic on Phase B is $3·0 \times 80/1\frac{1}{2} = 160$ v.p.h. Similarly, for Phase D, cycle-part 5 is omitted 8 times, so that $e^{-m} = 8/80 = 0·1$; hence $m = 2·3$. The traffic is therefore $2·3 \times 80/1\frac{1}{2} = 123$ v.p.h. For the pedestrian calls, the method can be rough only, since persons arriving during the minor-road periods tend to cross without making calls: but the number of cycles in which the pedestrian period was omitted was 15, and similar working

leads to the suggestion that about 90 calls per hour were made. It would be interesting to know whether the observations from which Fig. 17 was plotted included traffic volumes, and, if so, whether these are in substantial agreement with the figures quoted.

Mr. E. A. J. Bryan: On page 133 the author mentions three methods of measuring vehicle impulses, each of which he seems to criticize and find unsatisfactory, but he does not tell us which method he finally used. I should have thought that a siphon recorder or undulator such as was formerly used in machine telegraphy would have been a useful instrument, sufficiently sensitive for the purpose and reasonably portable. Time-base calibration could be obtained from the speed of the paper tape. On the other hand, a 50-cycle wave-trace, where such a supply is available, would serve the same purpose.

On the same page the author states that an important feature is that the whole of the switching is effected by relays, but he does not say a great deal about the relays themselves. Fig. 15 serves to indicate the wide variety of functions which these relays have to perform. If serious traffic congestion is to be avoided, reliability is essential, and, though the circuits are designed to prevent dangerous conflicting indications, the aim must be to provide apparatus which is as far as possible fault-free. It is fortunate that, as Mr. Anson has pointed out, a design of relay developed principally in connection with telephone apparatus is available which is capable of meeting these requirements adequately and which has proved its reliability in practice. It will be recalled that the President, in his Inaugural Address,* referred to fault analyses which revealed that a standard as high as 1 fault in 40 years can be expected from these relays.

I should like to outline the methods which are adopted in connection with traffic-control equipment to secure in full these desirable qualities. The relays used have two types of contact: the large ones are used for controlling the lamps, and the smaller contacts, which are arranged just below near the armature, are used in connection with circuit switching. The springs are supported on a " buffer block "; the moving spring pushes the buffer-spring off the steps of the block and transfers to the contacts any pressure which may have been previously adjusted on to those steps. This feature applies in each direction, whether the relay is in the release position or is being operated.

These principles of construction enable precise and permanent adjustments to be applied, which in turn permit very accurate forecasting of the performance of a relay with known and adequate safety margins. A very large number of combinations of these contact actions— make, break, and change-over, together with the special makes or breaks used for lamp switching—is required in one of these complicated circuits, and I should like to indicate the way in which factors of safety can be applied in design.

Each of the actions can be represented by an equivalent dead-weight load, and it is possible with any given combination to determine the total load which the relay will be called upon to operate. It is assumed that the load is applied to the armature, and that the armature has to operate or hold that load. From a series of load/ampere-

turn characteristics based on a large number of typical relays the ampere-turn values for a given load can be ascertained; these characteristics, being based on typical relays, represent the ideal, but as this is rarely met with in practice it is necessary to apply factors of safety to cover manufacturing variations, resistance tolerances, and voltage variations. These factors of safety are arranged to operate upon the load values. Such an arrangement ensures more constant results than would be obtained if the factors of safety were applied to the current values, owing to the bend in the characteristic, which exhibits the usual flattening due to saturation effects.

Windings are chosen so that with the voltage at the minimum extreme the energization will be sufficient to lift 4 times the equivalent load, i.e. we have a factor of safety of 4. This means that a relay designed for a voltage of, say, 50 volts, will not begin to fail until the voltage falls to about 22 volts. It is interesting to note that a controller designed for 220-volt supply was tested on 110-volt supply and, apart from the obvious necessity for adjusting the potentiometers to correct the timing, all the relays performed satisfactorily. To ensure a margin between factory tests and circuit conditions, electrical tests are applied in the factory based on a factor of safety of 2, so that there is a margin between the factor of safety of 4 in the circuit and the factor of safety of 2 in the factory. These tests are applied after complete mechanical adjustment, and no modification of the adjustments is permitted to meet the electrical tests. Similar methods are adopted in determining the holding and releasing condition, except that in this case the characteristic is dependent on the residual gap between the armature and the core. Speed of operation and release can also be calculated; this is important in connection with pulse generation. The speed depends on three variables—the residual gap, the size and position of the copper slug fitted to the coil, and circuit conditions. A series of characteristics have been prepared to cover these variables, and thus it is possible to predetermine the speed.

Mr. D. A. de C. Bellamy: The imaginary time-and-distance diagram shown in Fig. 21 does not give any indication of the difficulties which are likely to be met with in practice. For example, a through band of about 50 % is shown and it is clear that, had Canary Street been in a different position, say at about the 750-ft. mark, the diagram would have been wrecked.

In practice the conditions to be dealt with are like those of Oxford Street, where some of the intersections are close together and some far apart, and where, I think, one would be very lucky to have a through band of even $12\frac{1}{2}$ %. The result is that people enter the system at the wrong place and one is bound to have stops in places where one does not want them.

Fig. 24 shows that in none of the trial runs across Duke Street, James Street, and Davies Street was the journey uninterrupted, and the same applies to Berners Street and Newman Street. This was evidently entirely due to the extreme difficulty of getting a band at all through those sections of Oxford Street.

Unless the traffic engineer is able to produce a reasonable time-and-distance diagram, all the skill of the electrical engineer goes for nothing.

Mr. S. G. Purkis: There is only one small point in this paper to which I desire to refer, namely the manner in which the efficiency of a progressive scheme should be judged: that is to say, if one was dealing with the speed through the progressive system, whether one should take the time from the instant at which the vehicle arrived at the first junction or whether one should wait until the signal turned green, if it happened to be red when the vehicle arrived, and then start the timing. With the author's system the traffic is not admitted until the time has arrived when it can be guaranteed a free flow throughout the street; whereas there may be other systems where the object is to get the traffic into the system at the earliest possible moment, without any phase relation between the two ends, and then to stop it, either in the easterly direction or in the westerly direction or in both, at some point in the middle which will be convenient for sorting it out. The method of timing employed is probably dictated by the method of progression which is favoured.

I should like to refer to the point raised by Mr. Preist in regard to wear of road material on the remote side of the detector, due to the hump. So far, in my experience as a highways engineer, I have not seen any sign of such wear. The same speaker raised a point with regard to the justification of the " first come, first served " principle; local authorities consider this a very valuable feature, in view of the complaints which the general public make if they are held up at a traffic signal for more than 3 sec. when there is no traffic moving in the opposite direction. Mr. Preist referred also to the cycle-time increase bringing about a proportionate reduction in the progressive flow throughout the street. He spoke as though he was under the impression that the speed of flow through the street is proportional to the volume of traffic; actually the speed of flow is proportional to the cycle time, which can be set up to vary in any manner desired in accordance with the traffic volume, by the means which the author describes.

Mr. Anson referred to another point which is of very great interest to local authorities, namely unification of the control of signal maintenance. Travelling about as a private individual, I very often see signals which in my opinion are not maintained as they should be. Also, in the case of progressive systems, particularly where these end on the boundary between the areas of two local authorities, there is difficulty in making an improvement in the set-up of the system because it is impossible to convince the engineer of the adjacent authority that he is going to benefit by the change. The result is a deadlock, and perhaps nothing is done. From that point of view, it might be to the advantage of everyone if there were some unification of the control of maintenance.

Mr. R. Borlase Matthews: It would seem that road signalling has been developed from a different point of view from that of railway signalling, namely that of the police rather than that of the vehicle drivers. There appears to be too little standardization among the local authorities, a particular example of which is the differing times for the amber light.* For right- and left-hand turning it is unsatisfactory for the vehicle to have to

* Later, on the 10th November, 1937, it was officially announced by the Ministry of Transport that the duration of the amber light universally was to be 3 sec.

proceed against a red light (in some cases a green arrow signal is used on the first signal, but this is intended for infiltration purposes).

Again, has any consideration been given to audible signals which would warn the driver of a vehicle which had passed an amber light after a certain minimum period of time had elapsed? While motorists welcome the principle of signals, it is generally agreed by them that the present systems are still far from satisfactory.

A question which is not touched on to any extent in the paper is that of the maintenance of these equipments. It is very easy to call in a policeman when they do break down, but it should not be necessary to depend on the human element in that way. It would be well, therefore, to inquire whether there has been any development of the automatic replacement of defective parts by duplicates, with some kind of visual signal to show that these duplicates have come into use.

In the experience of road users, a very unsatisfactory part of a traffic-control system is the detector mat in the street, and it would be interesting to know whether photo-electric cells have ever been used as a substitute. Photo-electric cells are used for vehicle-counting; two cells are placed a short distance apart, so that they can record vehicles and miss out any pedestrians who happen to pass at the time. With regard to the street mats described by the author, it would help other engineers to know what is the composition of the material used to fill in the spaces around the nuts, screws, frames, etc. This material might be more suitable than present substances for street manhole covers, particularly those used in electricity distribution, as it is important to have a material which will fill up these spaces and thus prevent foreign bodies getting in but not make it difficult to lift the manhole.

The author's preference for signals at the side of the road rather than overhead signals is sound, but for occasions where there are two lines of traffic it is valuable to have in addition an overhead light which is well away from any neon-sign advertisements.

Some parts of the author's apparatus might well be adapted to the control of electric fences for keeping cattle in bounds. As only one wire and a few light supports are needed instead of a five-bar fence with many posts, the electric fence costs only about one-fifth as much as the ordinary fence, as well as being more effective. Over 30 000 farmers have installed these fences, using more or less suitable control apparatus. Much development work is still required on these controls, and hence the need for considering the possibility of utilizing a part of the author's apparatus.

Mr. A. Trigg: The section of the paper headed " Clearing Periods " shows a preference for the term " overlapping red " for the intermediate period during which all signals at an intersection show red, to provide a clearance period before giving the right-of-way to another traffic flow. To my mind, the term " all red " gives a much better mental picture of the conditions existing than the term " overlapping red," and, as the switching of all signals to red manually is done very rarely, I am inclined to think that it would be better to use the simpler and shorter term for the period more generally used.

On page 153 the author says: " The greatest number of intersections which can normally be traversed in a single journey is 5, this occurring in the New Oxford Street and Euston Road systems." I must disagree with this statement, because along Piccadilly there are 6, and in Glasgow there is a group with 8 intersections in it. Further, the two main streets of Glasgow, which run parallel, are each controlled in three groups with a total of 26 intersections on the two streets. As regards the relative times taken to traverse junctions under signal control and without signal control, some tests which the author made in Glasgow are very interesting. To traverse 26 junctions under signal control took something like 19 minutes, whereas before signals were installed the same journey took about 40 minutes. The change to signal control must have meant a big saving in running costs to the transport companies.

Mr. Taylor mentioned that the first vehicle-actuated signal to be erected in this country exploded. I would add that when the pieces of glass from the front panel were removed from the interior of the controller the unit went on satisfactorily controlling the traffic until a spare controller was provided some 5 hours later; this speaks well for the reliability of this type of equipment.

Mr. R. B. Hounsfield: I should like to refer to the author's definitions of the terms " prevent " period and " privilege " period in the section headed " Performance of the Local Controller." Both here and elsewhere these terms are defined in the order in which they occur in practice, and the reader has great difficulty in appreciating readily what the periods are intended to do. To make the definitions of these terms clearer it is desirable to go back to the author's statement (on page 141) of the fundamental principle on which flexible progressive working is based. He says: " The right-of-way must be available for the main-road traffic at the various intersections at the times indicated." This sentence should be immediately followed by the author's definition of the privilege period, namely: " The road having preference has the right of immediate response to its demands, and no change from this road is to be permitted." These two facts link together very well.

My next point is this: If a vehicle coming along the main road strikes the intersection during the privilege period, how can we guarantee that it can always force a right-of-way? It is not possible always to take the right-of-way at any moment from a side road because that side road has a minimum green period which, as the author explains, must first expire. It is not possible to " hurry up " that minimum green period; it is only possible to ensure that the side road does not get right-of-way so soon before the beginning of the " privilege " period as to cause trouble to the main road. It is therefore necessary, if there is to be a privilege period, to precede it by a period which the author has called a " prevent " period, in which right-of-way cannot be taken from the main road.

Perhaps he would say whether he considers that the method I have outlined would be an improvement on the ordinary method of defining these progressive periods.

Mr. A. J. N. Kennett: With regard to Fig. 2, it would be a great advantage if each of the signal lamps had a small coloured light at the side to enable the pedestrians to tell when the signal had changed. I myself have stepped right in front of omnibuses, and have even had the wheels touch me, through not knowing that the signals had changed.

Mr. E. S. Ritter: I agree with Mr. Kennett that the pedestrian aspect seems not to have received the attention which it deserves. I know a certain crossing which has a good deal of right-hand-turning traffic, and it has " Don't cross " and " Cross now " signals for pedestrians. The " Cross now " signal is a positive danger to pedestrians, because the traffic turning to the right has not cleared the crossing when the " Cross now " light is showing; and secondly, when the pedestrian is half-way across, the red " Don't cross " signal is given, the main-road signals turn to green, and the pedestrian is caught. It seems to me, therefore, that something on the lines of the amber light is required for the pedestrian, to give him some chance of getting across the road. In the case of the crossing to which I refer, the pedestrian has 12 sec. in which to cross the road, and the first 7 sec. are dangerous, because during this time the traffic is clearing the crossing. Has the author any way of curing this trouble, or of allowing a longer period to enable the traffic to clear the crossing before the pedestrian light shows that it is safe to walk across?

In the last part of the paper he refers to the measuring of the efficiency of systems; I suggest that the basis of these efficiency measurements is quite wrong, and that the criterion should be the number of accidents per mile of road per annum divided by the traffic density. Account should also be taken of the number of pedestrians killed and injured, in addition to vehicle collisions.

Mr. R. W. Palmer: I am greatly impressed by the importance which appears to attach to the time plan that precedes the design of any particular system, and particularly the progressive systems, but such a plan seems to have two weaknesses. One is that it is never achieved in practice, as anyone who tries to drive a car from one end of a busy street to the other will soon find out. The other is that the plan presupposes the division of the stream of traffic into alternate blocks of, say, 50 yards of traffic and 50 yards of space, and in the case of exceptionally busy roads it seems a pity to waste 50 % of the road by leaving it vacant. In congested streets the ideal would be to have the thoroughfare full of vehicles normally going through from end to end, and to stop the stream by simultaneously changing all the traffic signals at the intersections to red. Gaps would then be left for pedestrians to cross at each traffic signal, and the system would apply with equal efficiency and equal fairness at all vehicle speeds. At least it would have the advantage of simplicity, desired by several previous speakers. I should like to have the author's views on this system.

Mr. H. J. N. Riddle: I should like to support the plea which Mr. Preist has made for standardization of terminology, a matter to which several other speakers have referred. On page 129 some attempt is made to specify the meanings of various terms, but a very large number of terms could be added to the list there given. In considering this question it is well to remember that the

terms which are finally adopted will form the basis of traffic-signalling language; and the people who are going to speak this language are the Ministry of Transport, the police authorities, the local authorites, and the manufacturers. Until some system of standard terms mutually convenient to all these people is adopted there will always be a serious risk of misunderstandings. The author's definitions and the diagrams shown in Fig. 3 may represent means of overcoming difficulties which have been adopted by one of the sections to which I have referred, and not be representative of any general standard scheme. Referring to what Mr. Hounsfield has said about the privilege period, the question of a suitable phrase for this particular period was considered very carefully by the manufacturers.

With regard to the maximum green timer, it is possible to show that a predetermined and fixed maximum green period is not the best arrangement. It is possible, for instance, for 5 or 6 vehicles 5 or 6 sec. apart to run the maximum period to its full extent even though a great number of vehicles are waiting for the right-of-way on the other road. I feel that a scheme whereby the maximum green period can be governed according to some law, by the density of the traffic running during the right-of-way period on any phase, is worthy of careful consideration.

(*Communicated*) With regard to Mr. Preist's query as to the intensity of air pressures produced under certain conditions in the pneumatic system, and the possibility of the pneumatic bellows in the contact box bursting as a result of these pressures, experience has shown that no danger exists in this direction, and so far as my knowledge goes no instance of the bursting of these bellows has ever come to light with the equipment described by the author.

The question was also raised by Mr. Borlase Matthews of the type of compound used to seal the pneumatic mats during assembly. A red-lead and putty compound is used for this purpose and has been found to be very satisfactory. The screws which secure the tread in position are heavily zinc-plated and are greased before assembly. All exposed portions of the screws are painted, together with the metalwork of the detector, with a final coat of red-lead paint.

Mr. C. F. Wray: The author devotes nearly half of his paper to flexible progressive schemes, though the number of controllers in such schemes must be quite a small percentage of the total number of controllers in use. I think that in adopting this procedure he is probably indicating that he realizes the great importance of proper co-ordination in such a scheme.

I should like to say a word on the " vehicle-actuated " period. From Fig. 26 we see that the vehicle-actuated period of any phase is the time between the end of the privilege period and the prevent period of the next phase. During this period, normal vehicle-actuated changes of right-of-way take place except in so far as there is a bias for the road having preference. It would be of interest to know how the bias effect is obtained. I have in mind a fully vehicle-actuated flexible progressive system where the side-road traffic is of such volume as to have prevent and privilege periods of the nominal value to which the author refers, and in the first instance I should like to consider the case where right-of-way is on the side road and there is no traffic running. Any vehicle making a demand for right-of-way on the main road, with certain provisos as to minimum green and so on, obtains an immediate change of signals in its favour, but, unless similar conditions prevail at the adjacent junction, when the vehicle arrives there it is necessarily stopped. It would seem that, if these conditions prevail to a certain degree throughout the system, starting and stopping will occur due to the vehicle having got out of plan, and this may have further effects on the side-road traffic. No doubt the author has information, as the result of work and experience, which indicates that with such a system the apparent loss of efficiency due to vehicles getting outside their bands is not so serious as the delays which occur with a fixed-time flexible progressive system, but any information which he could give on this matter would be of interest.

[The author's reply to this discussion will be published later.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 15TH NOVEMBER, 1937

Prof. W. Cramp: I should like to ask the author why the colours red and green were selected for traffic signals. Everyone knows that the two colours which a colour-blind person will confuse most readily are red and green. Is it not possible to agree on colours more visible to a colour-blind person? I know of five male members of one family who are colour-blind and have had narrow escapes at crossings, which shows that some accidents are probably due to this cause.

Mr. A. N. D. Kerr: I should like to ask how the author would modify his system so as to make provision for controlling a greater number of crossings by one system of traffic lights. Would he consider the provision of independent generating plant, an alternative source of supply, or trickle-charged batteries? What precautions are taken to make the disturbance and inconvenience to traffic control as small as possible in the event of a failure of supply? In the particular case I have in mind the

traffic lights failed when the theatre traffic was disgorging.

I was very pleased to note that in the author's demonstration the relays were changed in 2 sec.; such a result is a tribute to the system.

Mr. T. A. G. Margary: When the first traffic signals in this country were installed at Wolverhampton the chief constable had to keep policemen on duty to explain to drivers how these signals were to be used. The first signal used was of the suspended type, but this was given up as, having to be mounted high enough to clear the traffic, it could not be seen by drivers. It was later replaced by a signal mounted on a pillar. In my opinion the mounting height of road signals is still too great as they cannot be seen with comfort from a saloon car, and I should like to ask the author whether there is any reason why they should not be mounted a little lower.

When motoring through a strange town I find it difficult to pick out the signals, particularly when there is much pedestrian and other traffic on the road, and I would suggest that the signals could be improved by placing a small flickering light on top to call special attention to them. Does the author consider this suggestion a reasonable one?

I should like to ask him whether any attempt has been made in this country to do away with the amber light. When I visited New York in 1927 I found that in the centre of the city the yellow lights were not used, as the authorities considered them unnecessary. The signals changed from one colour to another with an interval gap of perhaps not more than 0·5 sec.

Mr. D. E. Graham: The author showed an illustration of a Continental system with a clock face and a moving arm which gave some indication of the amount of the green interval still remaining, and he stated that such a device is not necessary in connection with a vehicle-actuated system. It would seem to me, however, that there is a possibility of using such an indicator even with the present system, because one can, even with a vehicle-actuated signal, approach a crossing and be caught half unawares. It could be so arranged that the signal which was going to change the lights could start off a motor-driven indicator which would reach the 12 o'clock position at the precise moment when the lights changed to red.

Mr. E. T. F. Onley: Is it possible to incorporate in traffic signals some device whereby the vehicular traffic can be held up from each end of a narrow bridge simultaneously, so that pedestrians may cross in safety? When a pedestrian is in the middle of a narrow bridge and a lorry with a wide load is passing, it is quite possible that the pedestrian may be swept off his feet unless provision is made for enabling him to get clear before the wide load is allowed to proceed.

Mr. W. R. Marsh: There are two types of control which the author has not mentioned and to which I should like to call attention. The first is a system of lights in which, for traffic coming in any one direction, there is only one lantern or projector to be seen. Whatever the signal, whether red, green, or orange, it is always shown through the same projector, which consists of a coloured slide having three definite positions controlled by a mechanism something like that which operates the lights of the more familiar traffic-control system. This type of signal overcomes the difficulty caused by the light from the sun, for it is possible for only one colour to be seen at a time, and it has the advantage of simplicity.

The second type of control is by means of a whistle of a rather high frequency, which is blown by a mounted policeman. The signals he gives are all the same, and serve simply to alter the direction of the traffic. This control system was used at a crossing in Chicago where the traffic was too dense to be able to move at speeds higher than 30–35 m.p.h. The system worked very well. I should like to know why audible signals are not more widely used, and why we have standardized on light signals.

Mr. A. W. Binns: The timing of all the systems mentioned by the author is regulated by a circuit

similar in principle to those employed in television apparatus for scanning, in which some form of thermionic relay is made to control the periods of charge and discharge of a condenser. The circuits shown by the author use neon tubes for this purpose, and it would be interesting to learn whether they have proved altogether satisfactory. Neon tubes are generally erratic in performance, and have been displaced entirely in scanning circuits by the more reliable thyratron, or by various types of gas-filled discharge tubes. Have experiments been made with other types of discharge tubes for timing purposes in traffic-control circuits?

It is very noticeable that traffic signals vary in size and shape in different localities; in view of the necessity for them to be easily seen and recognized by the motorist, has not any attempt been made at standardization?

Mr. N. M. Hill: It is sometimes said to be very easy to pass by mistake a signal on a sidewalk in a strange district. This difficulty does not arise in Berlin, where the signals are suspended 15 ft. to 20 ft. above the centre of the carriageway, and it is quite impossible to miss them. I have not seen such an arrangement in this country, and I should like to know whether there is any objection to it other than that of appearance.

Mr. T. G. P. Nettleship: The author refers to a high-speed relay; I should like to ask for further particulars of this relay.

It is noticed that tungsten contacts are used in his apparatus; it has been my experience that these are not very reliable, having a tendency to get "dirty." Possibly the special spark-quenching circuit and the use of rather higher contact pressures than are employed in telephone work solves this difficulty.

It is mentioned in the paper that the only difference between the Type 3 000 P.O. relay and the design used on traffic controllers is that the latter withstand a somewhat higher insulation test. From the author's slide there appeared to be little difference between the two, except for the top clamping plate of the spring assembly. Are there any other deviations from the P.O. Type 3 000 relay?

I should be pleased to have further information about the contacts in the pavement box, which in view of their dirty situation appear to have a difficult duty to perform. In this connection also I should be pleased to know where the control apparatus is housed, and whether any special precautions are taken to exclude dirt and dust.

Mr. H. Joseph: I should like to ask what weight of vehicle is required to operate the contact mat. I assume that a pedestrian, or a person wheeling a bicycle, would not be sufficient to operate it.

As regards unidirectional working of the mat, my understanding of this is that there are two bellows, one of which actually operates the contacts and the other causes the first bellows to lock so that it does not make contact. Is this correct?

Mr. H. W. L. Cowley: I am not quite clear as to how the clearance period is catered for when it is necessary for traffic turning right to be cleared from all four directions. I should like to know whether it is accomplished by separating each of the four detectors into two

or three sections, to regulate the dense uneven traffic streams in London.

The question of the rotation of lights, which is usually asked during a driving test, puzzles many. I have seen in Coventry the amber colour alone, but more often together with red, when the lights were changing from red to green.

Mr. H. J. Sheppard: I should like to raise again the question of the position of the signals. There are still quite a number of intersections where the signal is in the middle of the crossroads and not in the more usual position at the side of the road. I suggest that in spite of all the author says in the paper there are very real advantages in that arrangement from the point of view of the traffic. Thus the signal is farther from the traffic which is held up, which makes it easier to see; also it is less likely to be obstructed by other vehicles.

I should like to ask what type of protection is usually employed for the interconnecting cables in progressive systems. Are the cables pulled into ducts, or is armoured cable used? I have come across cases where an apparently unarmoured cable is run between the lights of an isolated intersection with no mechanical protection at all. It seems to me that this practice will tend to reduce reliability, which is so desirable in these installations.

Mr. J. E. Woollaston: I should like to mention the case of a crossing one approach to which is steeply inclined. Suppose that a heavily laden lorry is ascending the incline and that before it reaches the detector mat a demand occurs on the crossing road, and right-of-way for the lorry is removed. In such circumstances and on a frosty day I have seen a lorry unable to restart, and I therefore consider that vehicles on the incline should be allowed to retain right-of-way. This could be accomplished by arranging the mat farther down the incline, so that time would be given to clear or stop traffic on the crossing road. Do manufacturers cater for situations like this?

Mr. R. H. Rawll: An awkward situation arises when a vehicle is parked so close to the mat that it is impossible for the wheels of another vehicle to pass over the mat and thus operate the signals to give right-of-way. Is there any way of overcoming this difficulty?

Mr. H. Hooper: Has the author percentage figures for the number of failures spread over a year, for the type of apparatus described in the paper? Such figures would give us some idea of the cost liable to be incurred by way of maintenance.

What is the longest period of time allowed in any system for the signals to pass from red through amber to green?

What are the usual voltage conditions under which traffic-control apparatus has to work in various parts of the country, and have variations in the supply voltage any effect upon the operation of the relay system?

Mr. H. G. S. Peck: The traffic signals described by the author are of interest to telephone engineers from two points of view. First, because the Post Office provides the underground cables for interlinking the controllers; and secondly, because much of the apparatus used is automatic telephone switching apparatus. The relays were designed by telephone engineers, and the method of mounting and of jacking them in and out was devised by one of the telephone manufacturers. To keep such relays in good condition it is the practice in the Post Office to test them and to apply routine inspections and checks. Has this been found necessary in connection with relays for traffic controllers?

I am rather puzzled to find that in Shrewsbury the traffic lights are switched out at night-time, and driving feels to me much less safe when the signals are not working. I have noticed that when the signals are switched out in some towns an orange globe is illuminated on the top of the post; why is this plan not more generally adopted?

Mr. T. H. Varcoe: Relays for traffic-control work must be adjusted so that they operate at the correct instant to within a fraction of a second, and it is therefore essential that the voltage on the relays should be as nearly stable as possible. Can the author give us any information as to how allowance is made for variations in voltage of the supply mains, so that these very nicely adjusted relays shall act infallibly?

Mr. F. O. Hunt: Many years ago I put forward a suggestion to meet the dangers of colour-blindness. This suggestion took the form of a single illuminated signal arranged as an L, with red lights on the horizontal bar, green on the upright arm, and amber at the angle between. Such an arrangement would have the effect of a colour signal and a semaphore signal combined, without the troubles associated with mechanical moving parts. In those cases where the signal could be placed low enough in the centre of the road, i.e. where there is an island, it seems to me that it would be perfectly satisfactory.

I once had rather a peculiar experience in Worcester. The traffic lights showed green for me and I was going through quite happily, when from a narrow side-road a big herd of bullocks came out. As they were closely packed together it seemed impossible that they could have got across without touching the mat, but this must have happened, or probably the first one actuated the interlocking bellows and prevented contact from being made. Is there any way of avoiding such an occurrence?

Mr. J. A. Cooper: With reference to the remarks made by Prof. Cramp, it should be recognized that this is a very conservative country and I doubt whether many of us, in spite of the good case which he has made for changing the colours of red and green, feel very hopeful that a change will be made. There is, however, a case for the light signal to be accompanied by some other visual signal such as a semaphore to be operated by the light-changing relays. With some signals it is physically impossible to see which light is showing when the sunlight is coming from certain directions. Shades are provided by the manufacturers, but they do not seem to be effective at certain times of the year. If, associated with the coloured lights, we had a semaphore arm, then whatever the direction of the sunlight and however colour-blind the motorist, the additional signal would be understandable under all circumstances. Perhaps the design of the car traffic indicator could be modified to suit light-signal operation.

Secondly, could the words " stop " and " go " on red and green lights be arranged as clear glass, and not be painted on in black? The black letters do not show clearly.

Lastly, I have found that if one of the signal posts is

knocked over through a collision, the lights fail on all posts at the crossing. Traffic then rapidly becomes more and more congested until a policeman arrives on the scene to deal with it. In this way one accident may lead to others. Would it not be possible to design the signal-light posts so that if one were knocked over it would not throw all the others out of action?

Mr. D. Kingsbury (*communicated*): It has always seemed to me a pity that little or no effort is made by the authorities to persuade traffic on wide roads which have been marked out into lanes to use the near-side lane unless it is already occupied. It would appear that vehicle-operated signals could be used to bring this about. For instance, at intervals detectors might be placed in the near-side lane and also in the next adjacent lane, and signals operated by these detectors could be so arranged that if the outer detector were actuated without there being an impulse from the near-side detector within a given time before or after, the traffic in the outer lane would be pulled up or sent back into its proper lane by suitable signals.

[The author's reply to this discussion will be published later.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 30TH NOVEMBER, 1937

Mr. T. S. Parkinson: I can endorse the author's observations as to the success of the " pad " in the vehicle-actuated traffic signals. When this type of signal was first installed in St. Helens I certainly had some qualms concerning the road pad, but up to the present time it has not been necessary even to look at a single pad.

It appears to me that there must be a certain amount of traffic on a road before one is allowed to install traffic signals; but, on the other hand, either the police or the Ministry of Transport may decide that there is too much traffic in the section for signals to be installed. This seems to require an explanation, for apparently the electrically-operated robot is purely intermediary. As a supply engineer I should like to see every policeman taken off point duty and replaced by the electrical robot; but, to qualify this remark, one does feel from time to time that the policeman on point duty gets very annoyed if a waiting motorist should accidentally touch his horn contact, whereas the robot takes no notice.

Mr. G. L. Tomlinson: I associate myself with what Mr. Parkinson has said. There has been a great improvement in traffic signals during the last few years. When I was at Blackburn, before St. Helens, we had some signals operated by means of a motor and they were a great nuisance. I should like to ask the author whether at the present time there is any standardization of the signals themselves and of the quality of the glasses used. I know that difficulty is very often experienced in sunlight with these signals.

Dr. J. Robinson: I notice that the author practically ignores the fixed-time signals. I think that most members of Highway Committees consider such signals to be quite out of date, yet there are still a lot of these obsolete signals holding up traffic on the roads. No policeman can control the traffic as efficiently as automatic signals. One advantage of the vehicle-actuated system, with the variations that the author has noted, is that it can deal with " staggered " crossings, which certainly are a great problem; and an advantage of the system is that it can be modified to suit the different conditions. The author refers to the fact that it can be fitted for other than square or four-point crossings. Considerable difficulty is experienced at Old Trafford owing to the awkward angles at which certain streets meet and the great diversity in the amount of traffic in them. Another difficulty arises where two old-fashioned streets come in almost parallel and where one side is not visible from the adjacent street on the right-hand side. One method of control would be a signal suspended over the middle of the street, somewhat like the early ones the author showed, in which a horizontal band of colours gradually rotates, indicating how long the light will last before it changes. Whether that would be effective on some of these complicated crossings I do not know. I wish that motorists would put more pressure on local authorities by writing to the highway authorities and town councils to get on with the mechanization of the control of traffic.

Mr. Alfred Morris: On the maintenance aspect of these systems, can the author tell us which of the three main items—the signals, the controllers, and the detectors—gives the most trouble? What is the effect upon the traffic control of a very long length of road having a multiplicity of these signals, if one signal gives rise to considerable trouble? Is the whole system put out of gear? If not, how is the mis-operation or failure of a single item obviated so that the general behaviour of the system is not seriously impaired? I should also like to ask whether the author has any figures indicating the degree to which the systems are free from trouble. It is pointed out in the paper that the basis of these systems is mainly equipment of a telephone character. We have also seen in the demonstration set that a large proportion of the items consist of relays and other telephonic equipment, and I should like to know whether the faults on the system are expressed in any definite way; for example, in a manner similar to that adopted in a telephone system, namely faults per station per annum.

I should also like to inquire as to the manner in which the work of development of these systems has been co-ordinated as between the manufacturer, the designer, and the traffic authority. Some years ago I sat on a British Standards Committee which was dealing with a specification for these traffic controls. Can the author give us his views as to the extent to which standardization is at present desirable, and what degree of standardization has been achieved to-day? Are such committees, and the results of their work as expressed in these specifications, really of help to the designers and manufacturers of this type of equipment?

Mr. John Cyril Jones: What form do the charging resistances for the master controller take? If the value is of the order of 3 to 4 megohms, I should imagine they would be like those used for wireless volume control rather than of the wire type. Are the valves for obtain-

ing the time control of the conventional neon type or a special design? Also what governs the value of the striking voltage? It appears to me that the valve is a possible source of breakdown on this equipment, and it would be useful to have some indication of its life in actual service.

Mr. A. H. Gray: I should like to know why the signal has been taken from the centre of the road and placed on the footpath. When one is travelling behind heavy traffic the signal is completely obliterated; whereas, if it were on an island in the centre of the road, it would be immediately visible to anybody turning out to overtake traffic. At the same time this island would help to separate the lines of traffic and so conform with modern practice. The author has referred to tungsten as the metal used for contacts on his relays. As this is not the usual metal employed in modern relays, I should like to know why it has been preferred.

Mr. E. C. McKinnon: The title of the paper perhaps makes any reference to pedestrians irrelevant, but one cannot shut one's eyes to the fact that the introduction of traffic lights affects pedestrians very closely. The author may point out that the evolution of the traffic indicator is still in a stage of transition. Systems installed in various parts of London, for instance, may be designed to give the pedestrians some consideration. In the provinces, including large towns such as Manchester, there is undoubtedly at the present time an element of risk for the pedestrian at those intersections of main streets where traffic lights are installed. In fact it is difficult to say which is the more hazardous, to attempt a crossing controlled by a policeman or one controlled by a robot. The risk seems largely due to the prevailing practice of allowing traffic to flow at right angles to a stream of pedestrians attempting a crossing.

Traffic lights are sympathetic to the pedestrian in that a motorist can use his discretion and elect not to run down a pedestrian; whereas a motorist was recently in trouble with the Manchester police because after being beckoned on by the policeman at a crossing, he pulled up to avoid knocking down a pedestrian who had apparently not seen the policeman's signal and was attempting to cross the street. The motorist was told that he had got to obey the police signals.

My experience of traffic lights suspended over the streets in Berlin and Copenhagen has not been satisfactory; in fact, in the former city, policemen stand at the points where these traffic lights are installed, and the unwary pedestrian who omits to look up and observe these overhead signals is thereupon fined 1 mark. Traffic lights must be troublesome to colour-blind pedestrians. Has this been taken into consideration in any of the existing traffic-light designs?

Mr. R. B. Murray: I wonder whether any attempt has been made to synchronize signals in short lengths where there are a number of intersections, such as along Deansgate between Blackfriars and Peter-street, between which there are a number of intersections, at each of which a motorist might be held up.

Mr. A. M. Strickland: I suggest there should be some form of traffic signal to replace the rather ridiculous discs used on the roads whenever road work is in progress. These discs are very difficult to see, especially at night, and I think there may be a field for the development of a small and portable equipment for this type of work.

Mr. D. Palfrey: Can the author tell us whether the manufacturers have considered the possibility of incorporating some visual warning device on the control to show that the apparatus is working correctly? I have in mind a street intersection in the suburbs of London where, at certain periods of the evening, traffic on both roads is very light, but, owing to a short-circuit in the detector pad, one road had constant " green," giving the effect of a continuous traffic stream, while traffic coming down the other road had to wait until the maximum time-limit had expired.

Mr. P. A. Breton: Supposing something unusual occurs, such as a fire, so that one cannot have a straight road, is it possible to have remote control of the sections under consideration?

Mr. W. H. Lawes: It may not be generally known that the standard life test for a telephone relay is 20 million operations. If it fails once the Post Office are not satisfied with it: that gives some idea of the strenuousness of the test required.

Mr. A. Ridding: I should like to know in what manner control is effected for a tramcar.

[The author's reply to this discussion will be published later.]

HEAT LOSSES IN DIRECT-CURRENT ARMATURE WINDINGS*

By E. A. HANNEY, M.Eng., Ph.D., Associate Member.

SUMMARY

An account is given of an experimental investigation made on a direct-current machine, concerning current displacement (or, as some would say, eddy currents) in the conductors of the armature winding. The investigation is a sequel to a theoretical investigation previously published in the *Journal*.† The method adopted is that of making measurements of current density at several levels in the slot; the method is described with regard to oscillograms and also r.m.s. values. A series of results, obtained under short-circuit conditions, is reproduced, and it is shown that the oscillograms obtained represent variations of current density substantially in accord with those predicted from theory. The investigation was extended to cover open-circuit and full-load conditions, and results are reproduced. The necessity for further investigations is discussed, whilst tentative general conclusions are arrived at which should be of assistance to designers of direct-current machines.

CONTENTS

(1) INTRODUCTION

The direct-current machine is seldom the subject of attention on the part of investigators, apart from the manufacturers themselves. This may be due to widespread belief in a fallacy concerning the supposed obsolescence of direct-current systems and machines. During recent years, however, manufacturers appear to have been producing direct-current machines in greater quantities than ever before, and there is no sign of any impending change in this respect.

The present paper describes an experimental investigation which has been made in support of a theoretical investigation already published by the author.† All symbols and definitions of terms used in the present paper are in conformity with those adopted in the earlier paper.

The calculation of the loss which occurs in the armature of a direct-current machine, due to non-uniformity of the current distribution, is made with the aid of simplifying assumptions. [This calculation was discussed in Section (2) of the earlier paper.] The extent to which practical conditions violate the theoretical assumptions is likely to vary from machine to machine; and in one given machine it is likely to vary with the conditions imposed. The present investigation is therefore incomplete. The design of the machine on which tests were made is, however, such as to minimize some of the more obscure causes of current displacement.

The designer is interested principally in losses, and their direct measurement is difficult. A measurement of current densities at various levels is easier, and affords information as to the extent to which the theoretical treatment can be confirmed. The measurements were made by means of search wires mounted in one slot [see Section (4)]. The voltages expected in the search wires were not of sufficient magnitude to permit of direct measurement, and therefore amplifiers were built to allow the use of an electromagnetic oscillograph.

The experimental work was carried out in two sessions. The first programme was limited to tests in which the field windings were not excited, and a small driving motor was employed to obtain the necessary speeds. The second programme was carried out with the aid of a large driving machine, so that load tests could be attempted; at the same time r.m.s. measurements were made by means of vacuo-junction equipment. The necessity for completing each programme within a fixed period limited in some degree the variety of the tests which could be carried out; but the measurements made were thoroughly checked, and results could be repeated with very satisfactory agreement.

† *Loc. cit.*

(2) DETAILS OF THE MACHINE INVESTIGATED

The main dimensions and features of the machine are as follows: Number of poles, 4; armature diameter, 13·25 in.; armature core length, 9·625 in.; number of slots, 45; number of commutator segments, 225; slot section (see Fig. 1). Winding, progressive simple wave, $s = 1$, $n_a = 5$ (s = number of turns per coil in the winding, i.e. conductors in series per coil-side; n_a = number of coil-sides side by side in a layer in one slot), coil in slots 1 and 12, coil ends to commutator segments 1 and 114; slots skewed by 0·6 in. in the core length. Conductor size, two straps 0·045 in. by 0·25 in. arranged as shown in Fig. 1; replaced by a solid strap 0·045 in. by 0·5 in. in two taped-up coils only, these coils placed so as to have deep conductors throughout the slot in which search wires were fitted. Commutator diameter, 11 in. Four brush-arms, with 2 brushes per arm, each 0·5 in. by 1·25 in., grade " medium." Shunt field, two coils of 2 930 turns, and two coils of 1 980 turns. Series field, two coils of 6 turns, fitted on the poles with smaller shunt coils. Interpoles, four coils of 37 turns. Winding

Fig. 1

resistances, armature 0·084 ohm, interpole 0·028 ohm, series 0·0038 ohm, at room temperature. Interpole air-gap, 4·4 mm. with shoe 3 cm. wide. Main-pole air-gap, graded gap, with dimensions as given below ($\theta°$ is the electrical angle from the pole centre-line). 0°, 0·208 cm.; 10°, 0·213 cm.; 20°, 0·229 cm.; 30°, 0·254 cm.; 40°, 0·291 cm.; 50°, 0·35 cm.; 62°, 0·48 cm. An open-circuit test at 1 000 r.p.m. gave the following results: Voltage 500, shunt amp. 1·5; 440 volts, 1·08 amp.; 400 volts, 0·89 amp.; 375 volts, 0·76 amp.; 300 volts, 0·61 amp.; 200 volts, 0·36 amp.; 140 volts, 0·24 amp.; 90 volts, 0·13 amp. The armature is banded with high-tensile steel wire in the recesses, the recesses increasing the air-gaps by 0·24 cm.; there are five recesses in the core length, each 0·56 in. wide.

(3) SEARCH WIRES FITTED TO THE ARMATURE

The current displacement* is caused by the variation in flux linkages from level to level in a conductor. The phenomenon has already been discussed in the earlier paper.

The current density was measured at the top, the

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* Another method of considering this phenomenon is to consider an eddy current, superimposed upon the main current. This alternative would lead to the same results.

middle, and the bottom levels in the conductors; this required three search wires for one conductor (Items 1, 2, and 3 in Fig. 2) and also a single fourth wire (Item 4, Fig. 2). Each search wire was sweated to the conductor at one end of the armature, and carried along the

Fig. 2.—Suitable arrangement of search wires for one conductor, if the slot flux is normal to the slot sides.

side of the conductor at the same level throughout. If the flux across the rectangular slot is normal to the slot sides, the e.m.f. in the loop formed by the wire 4, the conductor, and a search wire, is pure resistance voltage-drop. An oscillogram of this voltage wave has ordinates proportional to the current density at the level of the search wire.

In a direct-current machine, current-changes in neighbouring conductors are not in phase, and there is a flux component which is not normal to the sides of the slot. Theoretically, this component is small [see Section (2) of the earlier paper]. But the oscillogram obtained from a search wire under given conditions varies somewhat according to the side of the conductor on which the wire is laid. It is therefore desirable to put search


Fig. 3.—Two search wires at the same level, one on either side of the conductor.

wires on *each* side of the conductor, at each level. If two such search wires at a given level are joined to make a short-circuited loop, the effect of radial flux through the conductor itself is eliminated. The arrangement is shown in Fig. 3, from which it is seen that the two search wires of a pair were kept separate, but closely twisted together, as far as the terminal board. This was to enable either wire to be uncoupled from the terminal if required. The search-wire current was very small; this fact, and the careful twisting of wires, made

it possible to assume that the e.m.f. available at the terminals is the arithmetic mean of the e.m.f.'s obtained from the two search wires separately.*

To find the wave-shape of the total current in a conductor, a fifth wire (Item 5 in Fig. 2) was soldered to the conductor, near the commutator, and the voltage-drop between Items 4 and 5 was recorded.

Conditions cannot be the same at the centre of the slot as at the side, and one of the objects of the investigation is to trace the difference between the current densities in conductors side by side, at the same level. Conditions are also entirely different for the two layers in a slot. In the body of one special slot, therefore, 24 search wires were arranged, in the positions shown in Fig. 4(a). The boundary conductors were left without search wires, owing to the great difficulty in insulating the whole taped-up coil in such a way that it could be pressed into the slot without damage to the
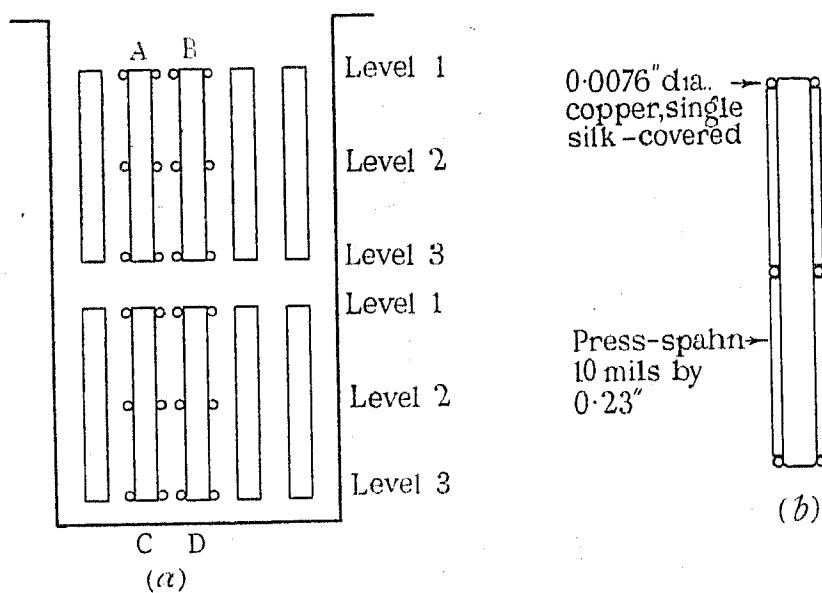
Fig. 4.—Arrangement of the 24 search wires in one slot, and insulation of a single coil, with search wires.

(a) View from commutator end.
(b) Search wires and strips placed in position on conductor when " tacky " with shellac. Outer wrapping of silk empire tape, half-lapped.

search wires.* The method of mounting the search wires and of insulating each coil is explained by Fig. 4(b). The taped-up coil is also wrapped with silk empire tape, half-lapped.

The two wires fixed to the conductor at one level were led off in close proximity, twisted together; three such twisted pairs, and the wire shown as Item 5 in Fig. 2, were twisted around the wire shown as Item 4 (of stout section, to act as a support) and brought out through the commutator spider to a bakelite terminal ring mounted on the outer end of the spider. Four such groups were brought out.

The search wires and the wires shown as Item 4 in Fig. 2 should ideally be fixed to the conductors where they emerge from the slot. Actually, the connections had to be made a short distance from the ends of the core; the effect of this modification is considered in Section (8).

* Tests were made to justify the doubling of the search wires [see Section (10)].
† A study of the test-results shows that there are many grounds for regretting the absence of search wires on the boundary conductors. Future investigators will doubtless pay due attention to these conductors.

(4) ARRANGEMENT OF PICK-UP WIRES

Brass slip-rings were mounted on the shaft near the commutator, and connections were made to terminals on the terminal ring. Each slip-ring had a semicircular groove to locate a pick-up wire of 0·028 in. tinned copper. Each pick-up wire was held by a helical spring at each end, and the springs were hooked to two supports bolted to the sides of the end casting. One of the supports could be raised or lowered bodily, to allow the wire tensions to be relieved whenever possible. Full wire tensions were applied for a minute or so for each test, and wear was slight so long as paraffin was dropped upon the contacts at frequent intervals.*

(5) EXPERIMENTAL CONDITIONS

It was shown in Section (3) of the earlier paper that the heating and current-density in a conductor depend upon the value of $|\alpha h|$; for a copper winding at $x°$ C. it was seen that

$$|\alpha| = 3·42 \sqrt{\left[\frac{f w_c}{w_s(234·5 + x)} \right]}$$

where f = frequency, w_c = total width (in cm.) of conducting material in one layer across width of slot, and w_s = width of slot. In this case $w_c = 0·225$ in. and $w_s = 0·359$ in. Hence, at 20° C.,

$$|\alpha| = 3·42 \sqrt{\left(\frac{0·225}{0·359} \cdot \frac{1}{254} \right)} \sqrt{f} = 0·17 \sqrt{f}$$

Also,

$$h = 2·54 \times 0·5,$$

whence $|\alpha h| = 0·17 \times 2·54 \times 0·5 \sqrt{f} = 0·216 \sqrt{f}$

Thus, at 20° C., the following values of K_0 are obtained (ratio between the heat loss due to a sinusoidal alternating current, and the loss which would occur if the current were uniformly distributed throughout the conductor):—

1 500 r.p.m., 50 cycles per sec., $|\alpha h| = 1·53$; $K_0 = 2$
1 400 ,, 46·6 ,, $|\alpha h| = 1·47$; $K_0 = 1·86$
1 200 ,, 40 ,, $|\alpha h| = 1·37$; $K_0 = 1·7$
1 000 ,, 33·3 ,, $|\alpha h| = 1·25$; $K_0 = 1·52$

These values of K_0 are rough estimates, allowing for winding particulars and chording, and using Figs. 9, 10, 11, and 15, of the earlier paper.

To avoid temperature difficulties, each record was taken as soon as possible after the current had been switched on. This time-interval could be made short, and the copper temperature would then be known within fairly close limits. (Low copper temperatures assist in increasing the value of $|\alpha|$.) It was calculated that at full armature current (about 160 amp.) the initial rate of temperature-rise in the upper layer of the armature winding at 1 500 r.p.m. was 1 deg. C. in 3 seconds. Single tests, made rapidly and carried out at intervals, allow a copper temperature of 20° to 30° C. to be used.

From Fig. 8 of the earlier paper and from the dimensions of the machine, a peak search-wire voltage of 275 millivolts was expected. This is too small for direct oscillography.

* The reduction of the rate of wear was not the most important function of the lubrication. Spurious e.m.f.'s were produced at the contacts whenever the lubrication became inadequate.

(6) APPARATUS FOR MEASURING SEARCH-WIRE VOLTAGES

The apparatus consisted of the amplifiers, the oscillograph, and the vacuo-junction apparatus for r.m.s. measurements.

(b) The oscillograph

An electromagnetic oscillograph was used, with elements of the high-frequency type. The frequency error of this oscillograph was not appreciable over the significant range. The records were made as a line of


Fig. 5.—Thermal instrument for r.m.s. measurements, and associated circuits for diversion of anode current.

(a) The amplifiers

The output currents of the amplifiers should be a faithful copy of the input voltages, but no appreciable power output is required. Two stages were incorporated, with resistance-capacitance coupling, and devoid of inductances. Each pair of input terminals was shunted by a resistance of 180 ohms, and the anode current of each output stage was carried by the associated oscillograph element. The results of various tests showed that frequency and phase distortion were negligible over the significant range of input amplitude.

bromide-paper strip, several cycles being recorded on each oscillogram.

(c) Apparatus for R.M.S. Measurements

A 10-milliamp. vacuo-junction was used, the steady anode current of 48 milliamp. being diverted from the vacuo-junction circuit. Fig. 5 shows the circuit used, and some hundreds of readings were taken without accident. It will be seen from Fig. 5 that a moving-coil milliammeter is included, together with a resistance equivalent to the heater of the junction. The steady
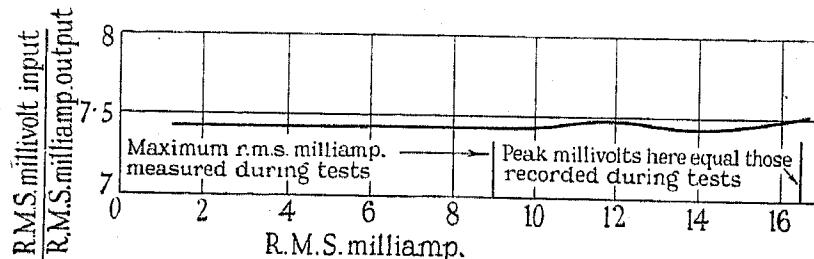
Fig. 6.—Typical response of Amplifier No. 2 and vacuo-junction apparatus to approximately sinusoidal voltage input.

The distortion produced by curvature of the characteristics of the output valve was not negligible, however. It became the practice to work with the minimum impedance in the output circuit, thus involving considerable amplitude distortion but maximum sensitivity. Oscillograms were subsequently co-ordinated, and corrected wave-shapes drawn by reference to calibration curves, which were plotted at frequent intervals throughout the tests.*

anode current may be neutralized before the junction is connected; the switch is then thrown over and the milliammeter brought exactly to zero* by adjustment of VR. The oscillograph element is included to act as a monitor. The signal was always viewed in the viewer of the oscillograph before application to the thermal instrument. This practice avoided the possibility of errors due to spurious e.m.f.'s, which appeared at the slip-ring contacts if the lubrication became defective.

* A calibration test was carried out by suddenly applying known voltages to the input terminals of an amplifier, the results being recorded on oscillograms exactly as test results were recorded.

* It was found that the readings given by the junction were scarcely affected by residual steady currents which were small relative to the alternating component.

OSCILLOGRAMS

CALCULATED CURVES

"Reduced" wave-shape, r.m.s. ratio = 2·4

R.M.S. ratio = 2·33

R.M.S. ratio = 3

Conductor B
Level 1

8 -
6 -
Ratio
4 -
2 -
0
-2 -
-4 -
-6 -
-8 -

Electrical angle

A B
Rotation
C D

R.M.S. ratio = 0·99

R.M.S. ratio = 0·96

Conductor B,
Level 2

("Reduced" wave-shape,
very close to this wave)

1 -
0
1 -

Commutation periods
for conductor and layers

6 -
4 -
2 -
0

R.M.S. ratio = 1·72

R.M.S. ratio = 2·06

Conductor B,
Level 3

"Reduced" wave-shape,
r.m.s. ratio = 1·65

-2 -
-4 -
-6 -

4 -
2 -
0

"Reduced" wave-shape,
r.m.s. ratio = 1·42

R.M.S. ratio = 1·61

R.M.S. ratio = 1·63

Conductor D,
Level 1

-2 -
-4 -

1 -
0
-1 -

R.M.S. ratio = 0·99

R.M.S. ratio = 0·96

Conductor D,
Level 2

1 -

R.M.S. ratio = 0·95

R.M.S. ratio = 0·91

Conductor D,
Level 3

-1 -

"Reduced" wave-shape,
r.m.s. ratio = 0·90

Fig. 7.—Curves of current density for the conductors on the centre line of the slot, with clockwise rotation (lower-layer currents leading by 4°); 50 cycles per sec.; $|\alpha h| = 1·53$; no main field; armature current 160 amp.
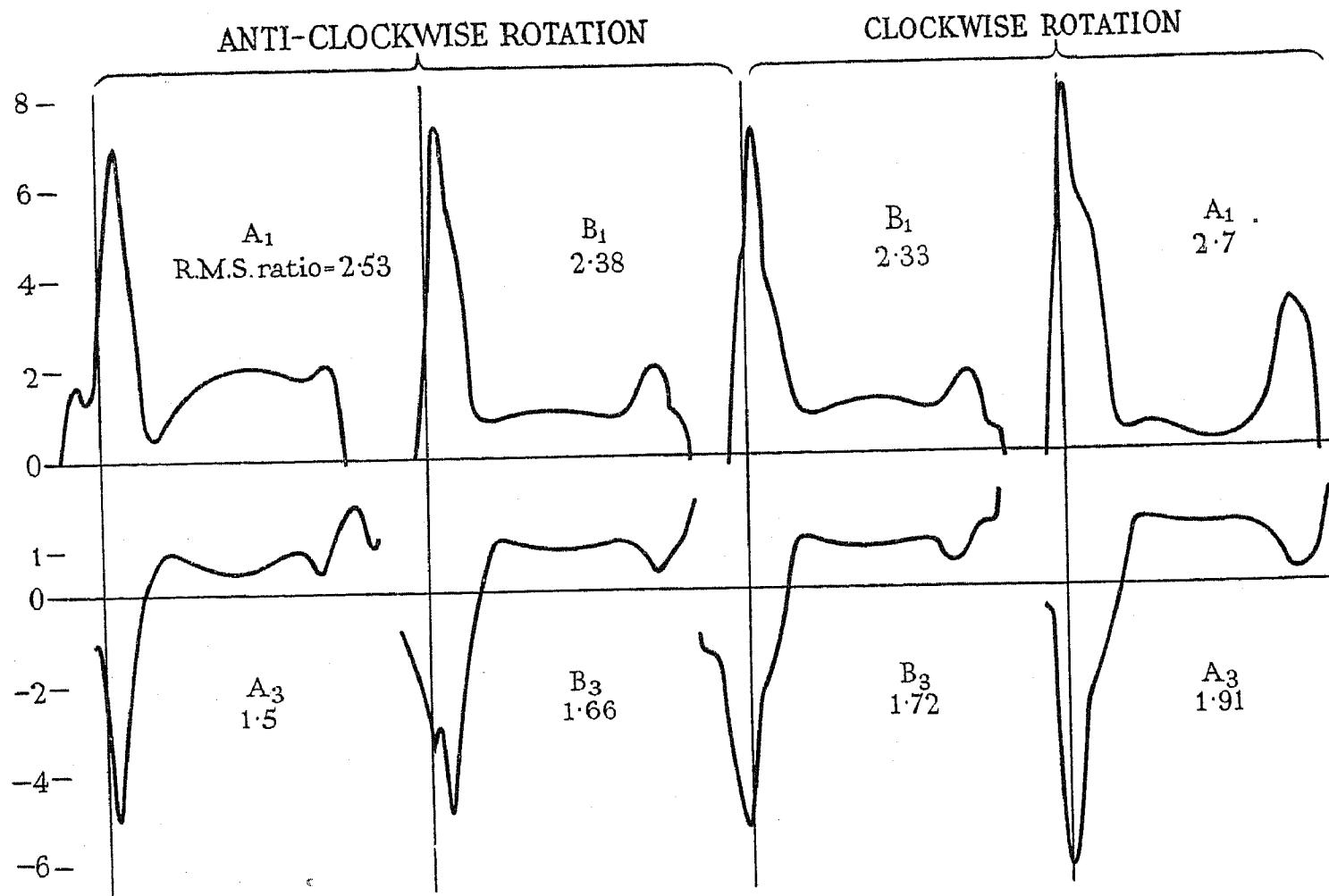
Fig. 8.—Records of current density for two levels of the upper layer; conditions as for Fig. 7.

Calculated and "reduced" calculated ratios: 3·075 and 2·48 (anti-clockwise), 3·0 and 2·4 (clockwise), for upper set of curves; 1·95 and 1·53 (anti-clockwise), 2·06 and 1·65 (clockwise), for lower set of curves.

A test is necessary to show that apparatus exhibiting amplitude distortion can be used to obtain useful r.m.s. measurements, the accuracy of which is sensibly independent of wave-form. A theoretical curve showing the r.m.s. values of pairs of responses, corresponding to pairs of equal and opposite input voltages, can be constructed from a calibration curve; it is very nearly a straight line, except for an appreciable divergence at the highest values of input voltage, corresponding to the highest peak values encountered during the tests.

The actual response curve of the apparatus to an alternating wave of input voltage must depend to some extent on the wave-shape, notably on the extent to which the momentary values of the input voltage dwell within the non-linear (i.e. the uppermost) regions of the curve. The signals measured in the tests have a high ratio of peak value to r.m.s. value, in all cases where the peaks are themselves high. The apparatus was tested by the application of known small alternating voltages of approximately sinusoidal wave-form, extending to peak voltages as high as any actually encountered. The response is shown in Fig. 6. Since the error involved in measuring the more peaky voltages met with in this work is likely to be less than is shown in Fig. 6, it was concluded that readings of the thermal scale of the millivoltmeter could be converted to r.m.s. values of voltage input by the use of a simple factor.

(7) ACCURACY OF MEASUREMENTS

The most important source of error is the lack of constancy of the amplifier calibration, and this could only be minimized by rigidly constant conditions, and by the frequent plotting of calibration curves. Ideal conditions could not be fully observed in this work, but the repetition of tests at intervals yielded results which never differed by more than 5 % from original results, and were usually well within this margin.*
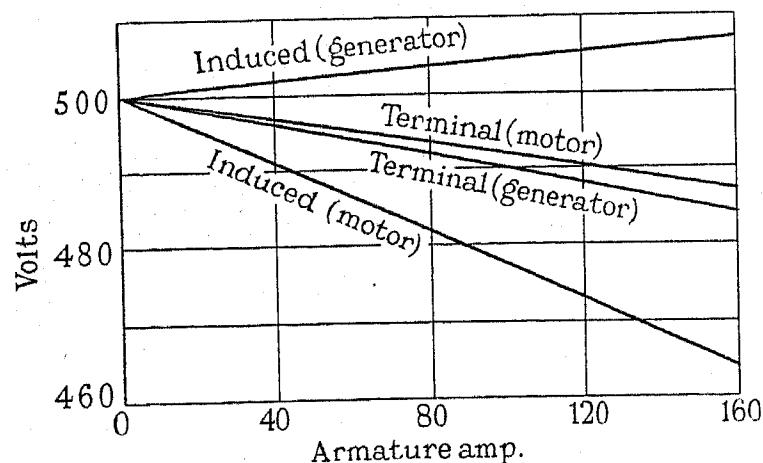
Fig. 9.—Induced and terminal voltages during load tests.

The thickness of the line in oscillograms can give rise to an error of 0·1 in the measured ratio value. This was reduced, for small values of the ratio, by multiple readings.

The values of the ratio given in the curves of Figs. 7, 8, 10, 11, and 12, depend on the figure in millivolts which

* This must be qualified by uncertainties which appeared to arise from the magnetic state of the machine. Thus after the machine had been subjected to high magnetization, succeeding short-circuit tests gave unreliable results until the new condition had been imposed several times.

is adopted to represent a known current-density in the conductors. The figure of 27 millivolts adopted to represent unit ratio at an armature current of 160 amp. was derived from potentiometer measurements; these were made with the armature stationary in several alternative positions. The figure is believed to be correct within 3 %.
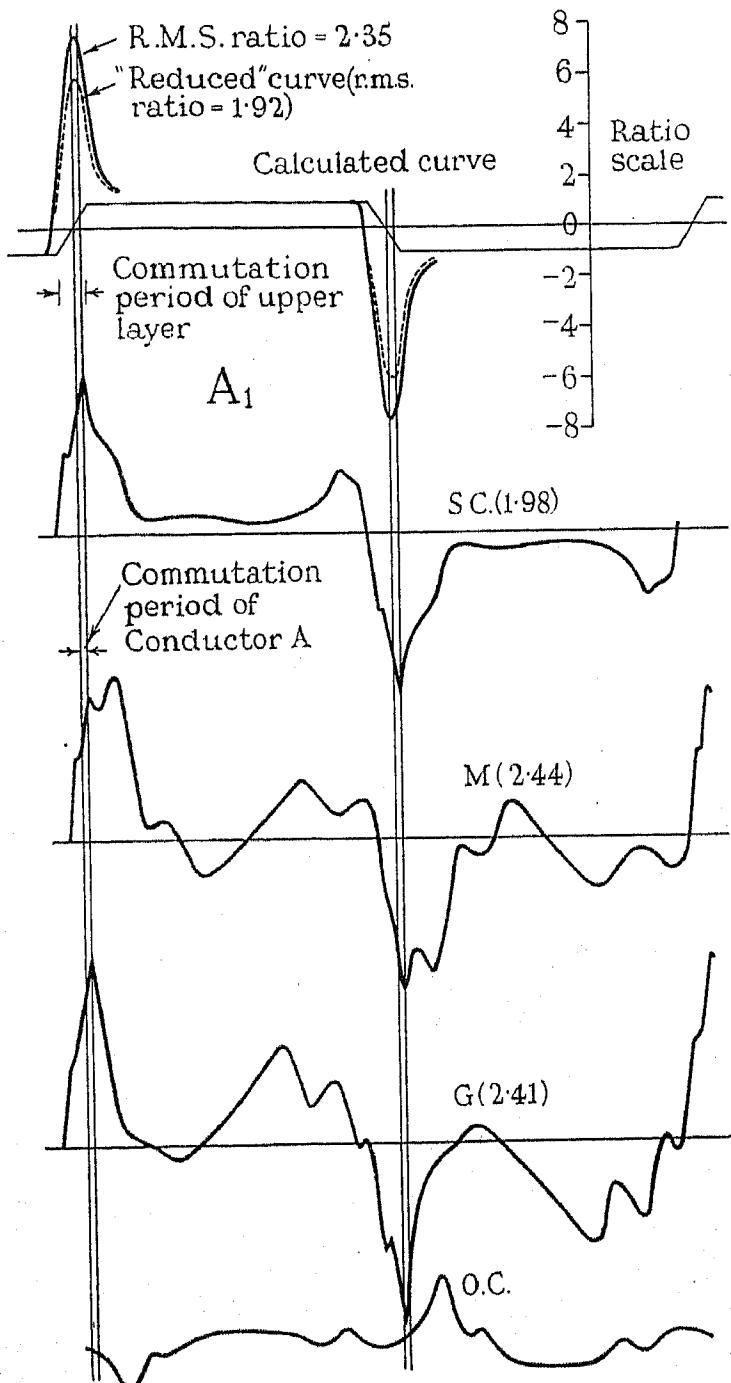
The shunt and series field windings were not used. The brush position had to be adjusted with care, and changed when the rotation was changed; otherwise an e.m.f. was induced between brushes and a torque was produced by the machine. This is specially referred to in Appendix 4.

Commutation was sparkless at all the currents em-
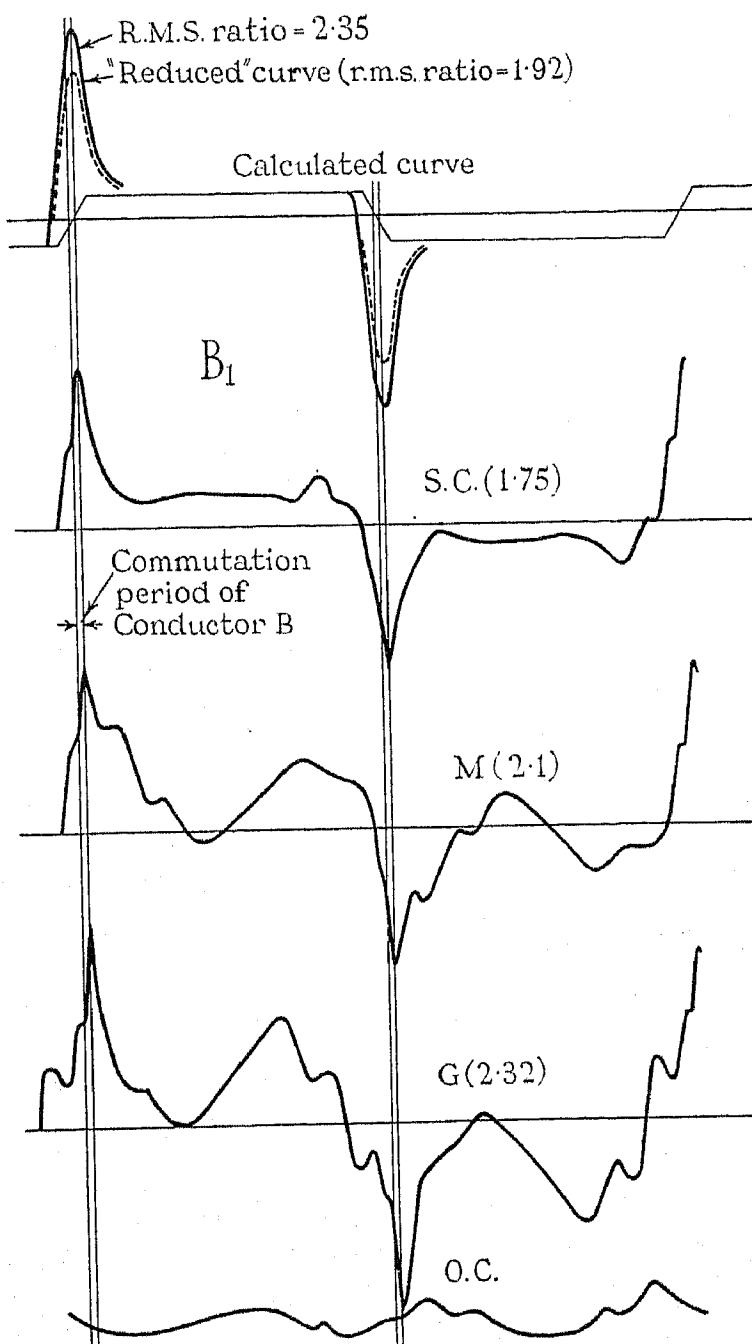
Fig. 10

Clockwise rotation.   Figures in brackets are r.m.s. ratios as given by direct measurement (Fig.13).   S.C. = short-circuit, M = motoring, G = generating, O.C. = open-circuit.   Commutation of A occurs after that of B.

(8) PART I OF THE EXPERIMENTAL PROGRAMME

The machine was driven at 1 500 r.p.m. by a 10-h.p. motor, which limited the possibilities of loading. Whilst it was believed that small main fields could be used to produce armature currents on short-circuit, it was decided to commence by feeding the armature from an external source, and a low-voltage heavy-current machine was used for this purpose. (It was found later that perfectly reliable results were obtained by using the machine on actual short-circuit; the small main fields employed have negligible effect on the result.)

ployed. The oscillograph records of conductor current were not capable of showing much detail during the commutation period, but commutation appeared to take place in a linear manner approximately. Special low-speed tests showed fair approximation to straight-line commutation.

Twenty-four results were obtained, at 160 amp., 1 500 r.p.m., one for each of the twelve search wires shown in Fig. 4, with both directions of rotation. Each result was obtained together with the record of conductor current, so that the period of commutation could be identified. The records inevitably showed differences

in time scale, and amplitude distortion was also present. A set of standardized curves was therefore produced, to a common time scale, with a common zero of time phase for the results of one layer, and to an ordinate scale representing current-density *ratios*. The curves were produced by hand methods, involving the tracing of a typical wave over one period; each wave was measured, and the time co-ordinates were changed to a standard time scale, whilst the voltage co-ordinates

and 8. Owing to the general similarity between the curves, only a few of the 24 results are shown. Thus Fig. 7 shows the results for one direction of rotation, for conductors B and D (on the centre line of the slot). The amount of variation from conductor to conductor at two levels is shown in Fig. 8; the degrees of variation in the lower layer are similar for Levels 1 and 3, but at Level 2 there is little variation.*

Calculated curves obtained by the method used in
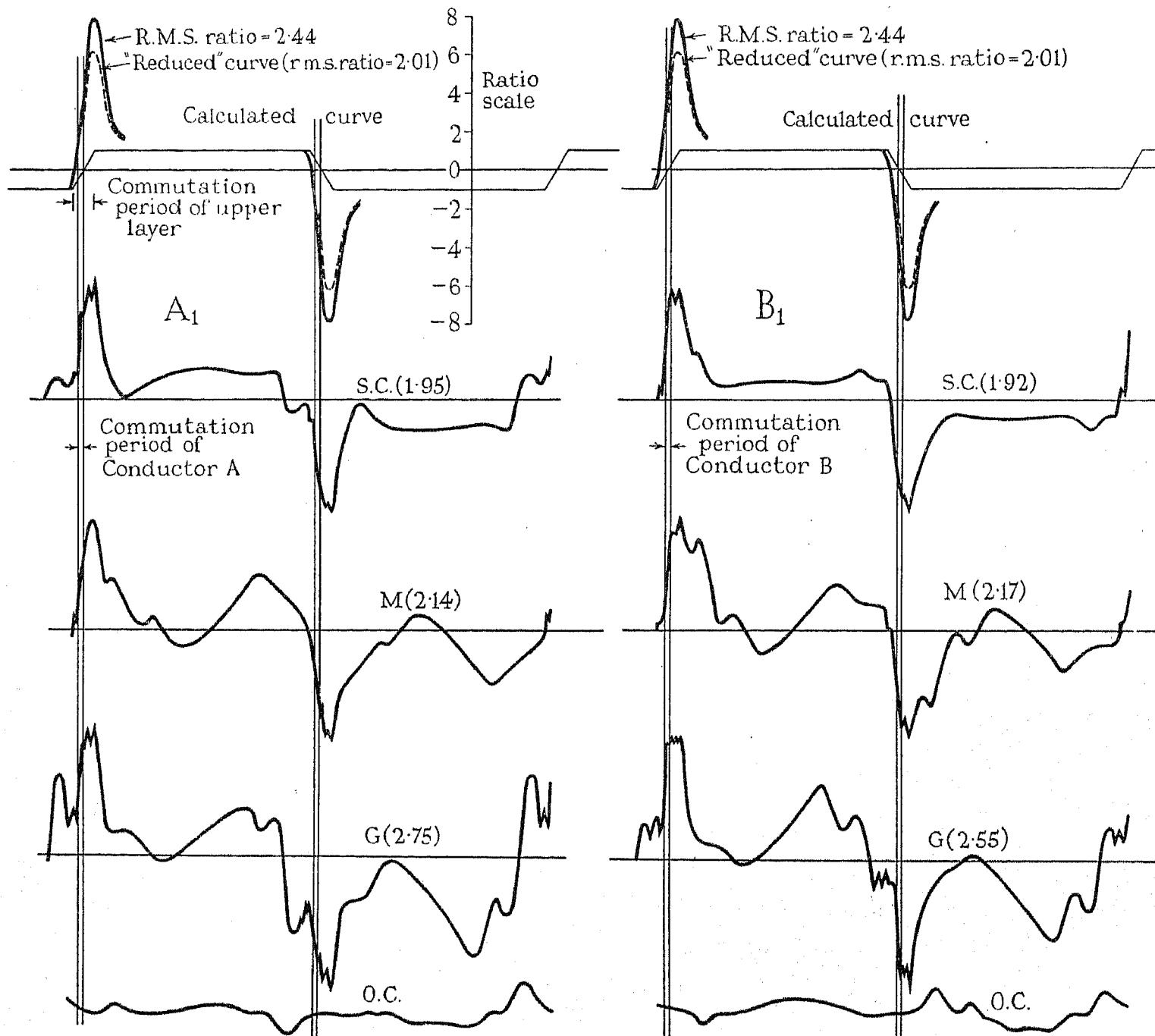
Fig. 11.

Anti-clockwise rotation.   Commutation of A occurs before that of B.

were changed by reference to a calibration curve of the amplifier and oscillograph. Finally, the corrected voltages were changed to ratios, the standard of reference being the voltage-drop measured in the search wires when the armature conductors carried 80 amp. (main current 160 amp.) of undisturbed current. This nominal voltage was actually measured from many oscillograms, portions of which represented undisturbed current; good agreement was obtained between these measurements, the calculated voltage-drop, and the figure given at the end of Section (7).

Some of the standardized results are shown in Figs. 7

the earlier paper are also shown in Fig. 7, due allowance being made for chording. The calculations are made as for a single conductor per layer, with a layer commutation period of 17° (electrical).† Owing to the

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* Theory indicates that in a chorded winding the direction of rotation has a small influence on the upper-layer results. The measurements actually showed differences which were in close agreement with the theory. Conductors A and C are nearer the slot boundary, and in general their current-density wave-forms show greater variations from the calculated forms, whilst their r.m.s. current-density values also show more variation.

† This figure of 17° is made up of $(4 \times 3 \cdot 2°) + 4 \cdot 2°$. There are 5 coil-sides in the layer, and the segment pitch is $3 \cdot 2°$. The figure of $4 \cdot 2°$ is representative of the 4° to $4 \cdot 5°$ commutating period of one coil, and is measured from oscillograms. The period calculated from the brush dimensions is $9 \cdot 8°$. This matter is referred to in Appendix 4. The coils are chorded $\frac{1}{4}$ slot, or 4°, and this is the amount by which the layers are out of phase.

labour involved, calculations include harmonics up to the 21st only, and do not cover the whole period.*

The broken-line calculated curves in Fig 7 are "reduced" from the full-line calculated curves allowing for the distance between search-wire connections being 3 in. longer than the core length; the assumption is made that no current displacement takes place in this 3-in. free portion. The method of finding the "reduced" values is not simple, since the wave-shape in a search wire at a given level follows the displaced current in the buried portion, whilst that in the free

(9) PART II OF THE EXPERIMENTAL PROGRAMME

General

The test machine was driven by another machine, the frame size of which was almost as large. Unfortunately it was not possible to obtain a driving machine similar to the first, and this limited to some extent the tests that could be carried out. Only a single d.c. supply was available, and for loading purposes a back-to-back type of test was necessary. In order to ensure a normal
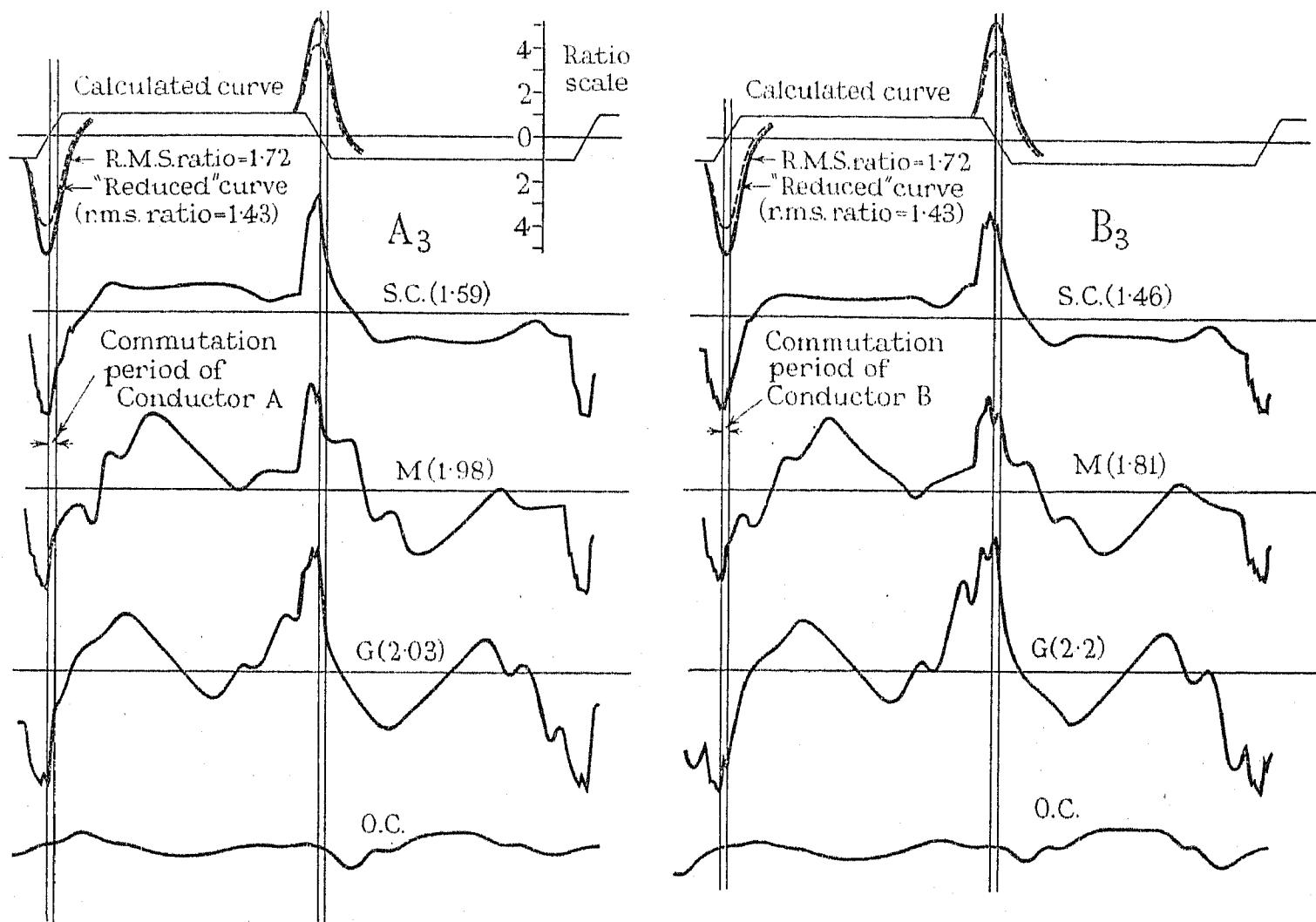
Fig. 12

Results for clockwise rotation. (For anti-clockwise rotation the results resemble those shown here, the order of difference being similar to that between Fig. 10 and 11. R.M.S. values are on the average 10 % less, but A_3 results are *lower* than those for B.

portion can only be assumed to follow the wave-shape of total conductor current. The explanation of the method is deferred to Appendix 1.

The discussion of these results is deferred to Sections (11) and (12), in which tentative conclusions are formulated. Many other tests were made at this time, at speeds other than 1 500 r.p.m., and currents other than 160 amp. A brief note on the results of the more important of such tests is given in Section (10).

degree of saturation in the machine during load tests, and at the same time to have maximum speed, it was decided to work at 500 volts and 1 000 r.p.m. for the main tests. Thus the driving machine had to operate with a weak main field, and this cut down the maximum load which could be applied to the test machine as a *generator*, and the maximum speeds at which tests could be made.

The tests consisted of open-circuit, short-circuit, and load (both motoring and generating) tests, in both directions of rotation, on all search wires; the armature current was 160 amp. (only 128 amp. for generating load tests), at 1 000 r.p.m.

For all load tests, the machines were paralleled at
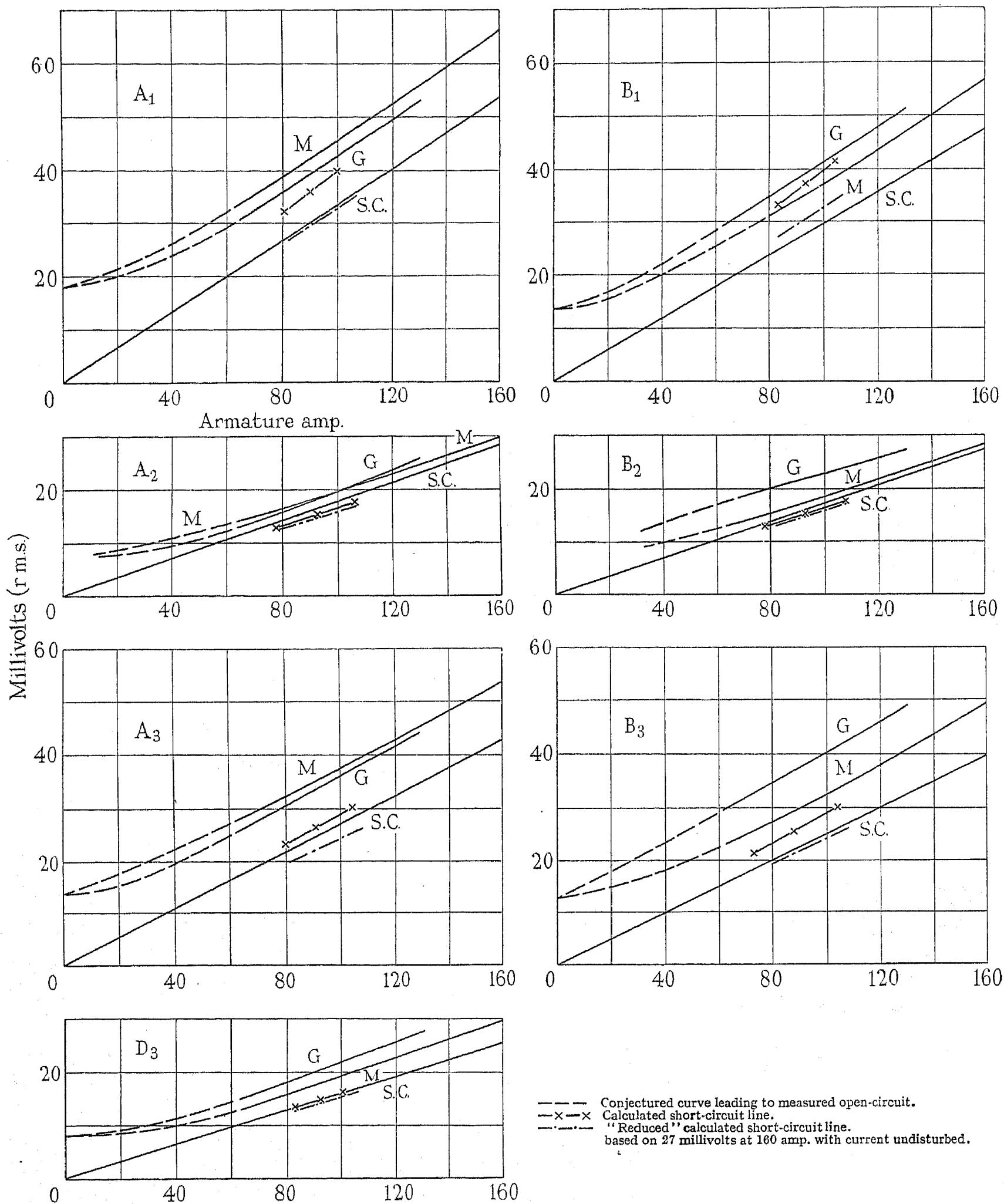
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* For the upper layer, the calculated curves for the two rotations differ slightly. This is due to the chording, which causes the commutation of the upper layer to begin before that of the lower layer, or after, according to the direction of rotation. Whilst theory indicates the same *total* conductor heating in both cases, differences occur at a given level in the magnitudes and phases of the current harmonics, so that the wave-shapes are not quite the same, nor are the distributions of heat production.

Fig. 13

G = generating, M = motoring, S.C. = short-circuit.
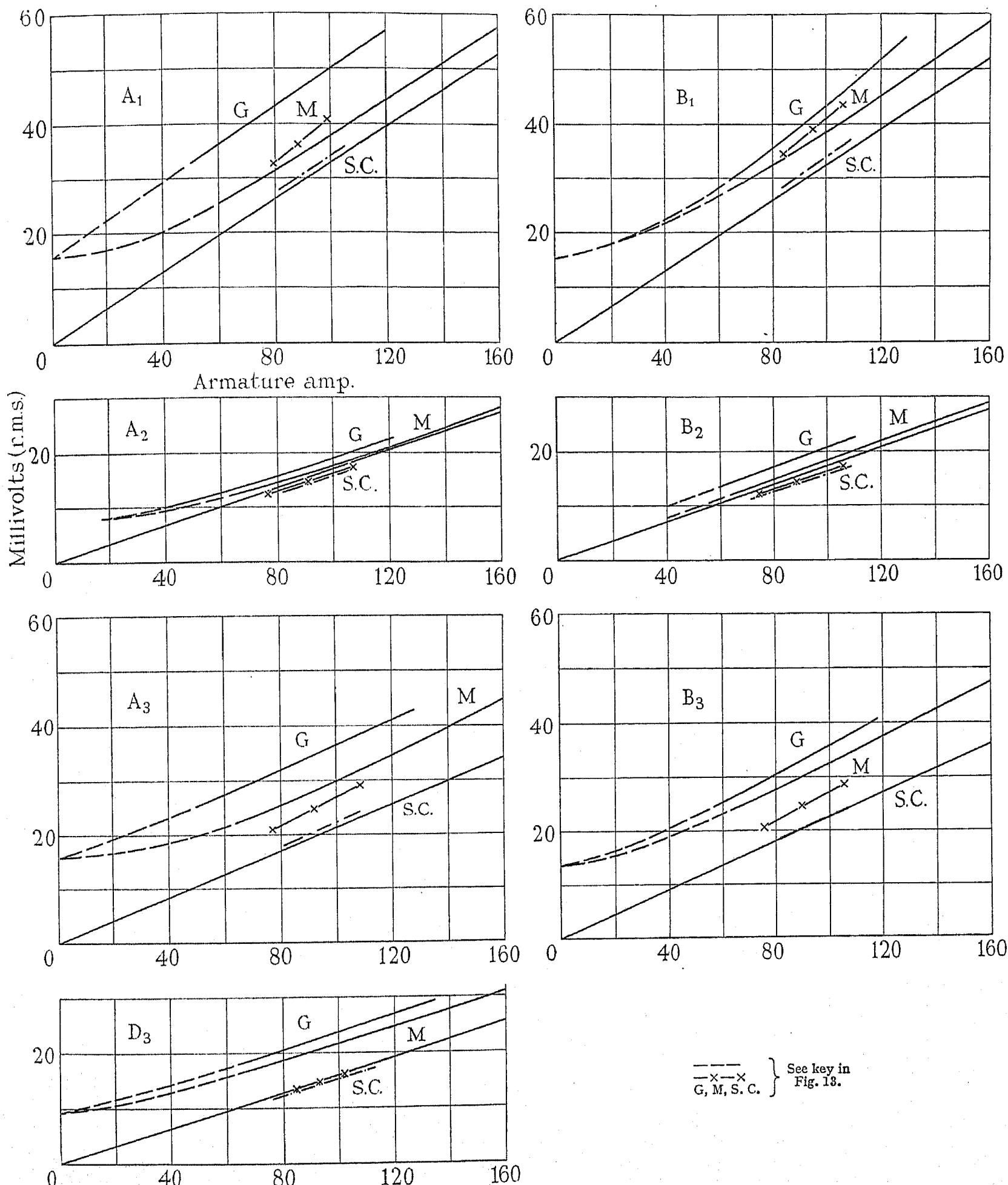
Fig. 14

Anti-clockwise rotation, 1 000 r.p.m   (Commutation of A begins before that of B.)

500 volts, and load was applied by field adjustment. The supply voltage fell slightly as load was applied, and the induced e.m.f. in the test machine was not constant. The oscillograms on open-circuit were recorded at 500 volts. Since the field distribution on load is profoundly affected by armature reaction, it was decided not to complicate the test procedure by any endeavour to keep to the same induced voltage for open-circuit, motoring, and generating tests. Fig. 9 shows the estimated induced e.m.f. and measured terminal e.m.f. over the range of armature current used in the tests.

Current-Density Wave-Forms

Sets of oscillograms were recorded, and these have been traced and standardized as in Section (8). Although the current wave-forms (and in some cases the coil-voltage wave-forms) were recorded, they have only been used to identify the correct phase of the current-density

1·02 on short-circuit, 1·07 on motoring load, and 1·18 on generating load; the effect on open-circuit was negligible.

The results for the lower layer are not reproduced, as they are in line with expectations based on the upper layer, and on the lower-layer results given in Section (8).*

The sawtooth characteristics of the curves for the full-load tests are discussed in Section (11).

R.M.S. Measurements

The results, converted to millivolts, are given in Figs. 13, 14, and 15, for tests at 1 000 r.p.m. Armature currents up to 160 amp. were employed, except in the generating tests. The lower limits of the currents were fixed, in general, by the lowest readings which could be made with any reliability on the thermal scale of the millivoltmeter. Further measurements were made, over a range of speed, on short-circuit (at 96 amp.) and on
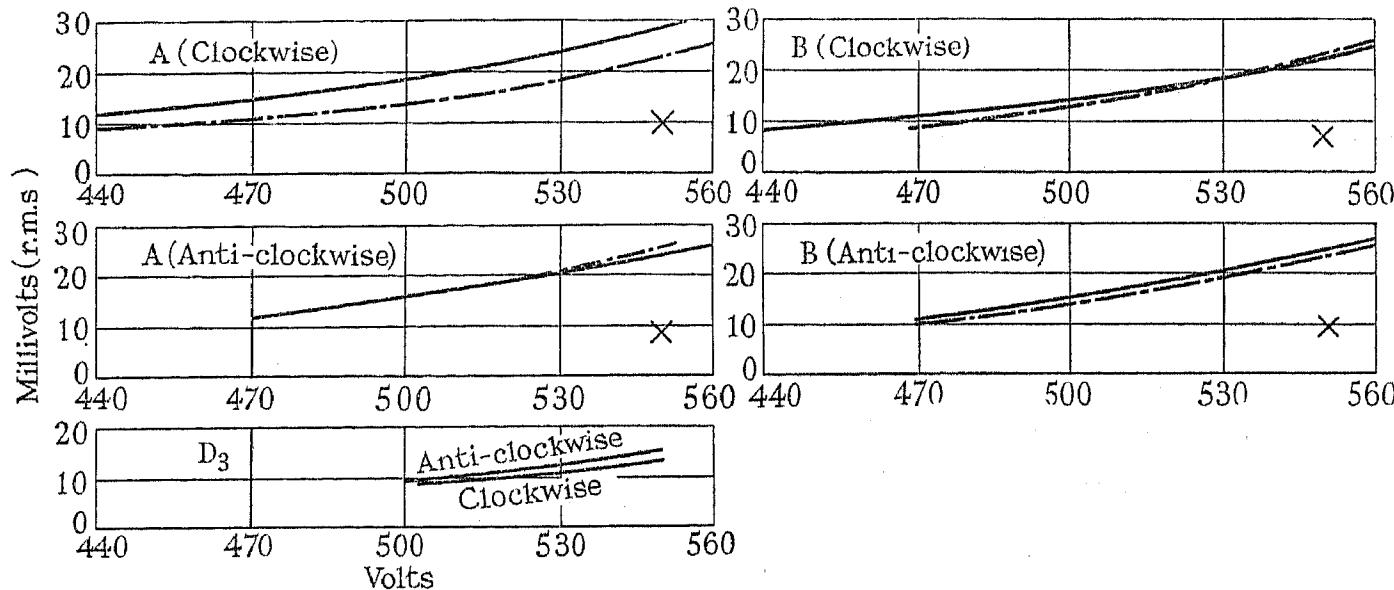
Fig. 15.—Open-circuit results, 1 000 r.p.m.

———— A_1, B_1.   —— · —— · — A_3, B_3.   × A_2, B_2.

27 millivolts denotes a current density equal to that due to an armature current of 160 amp. (conductor current 80 amp.) uniformly distributed.

waves, a matter of difficulty in some of the records. Figs. 10, 11, and 12, show some of the results, set out in a way which facilitates comparisons. All the currents are in phase, and thus the field in the motoring results opposes that in the open-circuit results. The calculated curves include those for the buried parts of the winding (full-line curves), and the "reduced" (dotted) curves those for the buried and free portions of the winding between search-wire connections [see explanation in Section (8) and Appendix 1]. With each calculated curve the trapezoidal curve of mean ratio throughout the layer is also shown, since this wave-shape is assumed for the layer current in the calculations. The curves are labelled with their r.m.s. values, and in the case of the oscillograms the values shown are obtained from the r.m.s. measurements described below; but, in all cases, the r.m.s. values of the standardized oscillograms have also been calculated from the curves, and a very satisfactory standard of agreement has been found. For the mid-levels of both layers, all the oscillograms were very similar to those shown for these levels in Fig. 7, the shape being almost independent of the load condition; whilst the calculated r.m.s. ratio is 0·965 ("reduced" ratio 0·93), experimental values averaged

open-circuit (high saturation). The results are given in Figs. 16, 17, and 18. The calculated millivolts are also marked on the Figures; these are the r.m.s. ratios, as given in previous results, multiplied by 16·2. This factor is proportional to the 27 millivolts adopted to represent the current density due to 160 amp. [see Section (7)]. The open-circuit results shown in Fig. 18 are only for Conductor A; those for B were similar, and slightly lower. For the lower layer, the incomplete results showed lower figures than for the upper layer, and many of them were too low for reliable measurement.

(10) FURTHER TESTS

The results already given are the most important of those obtained. Other tests of some importance are described below.

(a) Oscillograms at 1 500 R.P.M. (50 cycles per sec.) and Low Currents in Armature (No Main Field)

The peaks of current density appeared to be almost proportional to the current. Whilst the current-density

* It should also be stated that open-circuits occurred during the tests on a few of the search wires in the lower layer, and the results could not, therefore be given in full

waves at full current contain dips and excrescences, there was a general tendency for the wave-shapes to be smoothed out so as to approach more nearly to the shapes of the calculated curves, as the current was reduced.

(b) Oscillograms at Low Speeds, with 160 Amp. in Armature (No Main Field)

Records made at speeds down to 750 r.p.m. yielded wave-shapes which were not inconsistent with the " root frequency " law [Section (5)]. Low-speed tests, made at

occurred in Level 1 of Conductor A and amounted to about the normal current density given by 160 amp., with undisturbed current. It was concluded that the effects observed can account for some of the features which appear in the curves of Figs. 7 and 8, within the period of slot commutation, but do not account for the effects observed outside this period.

(d) Records of the Wave-Shapes of Coil Voltage

In many tests, oscillograph records were made of coil voltage. The wave-shapes are very nearly records of
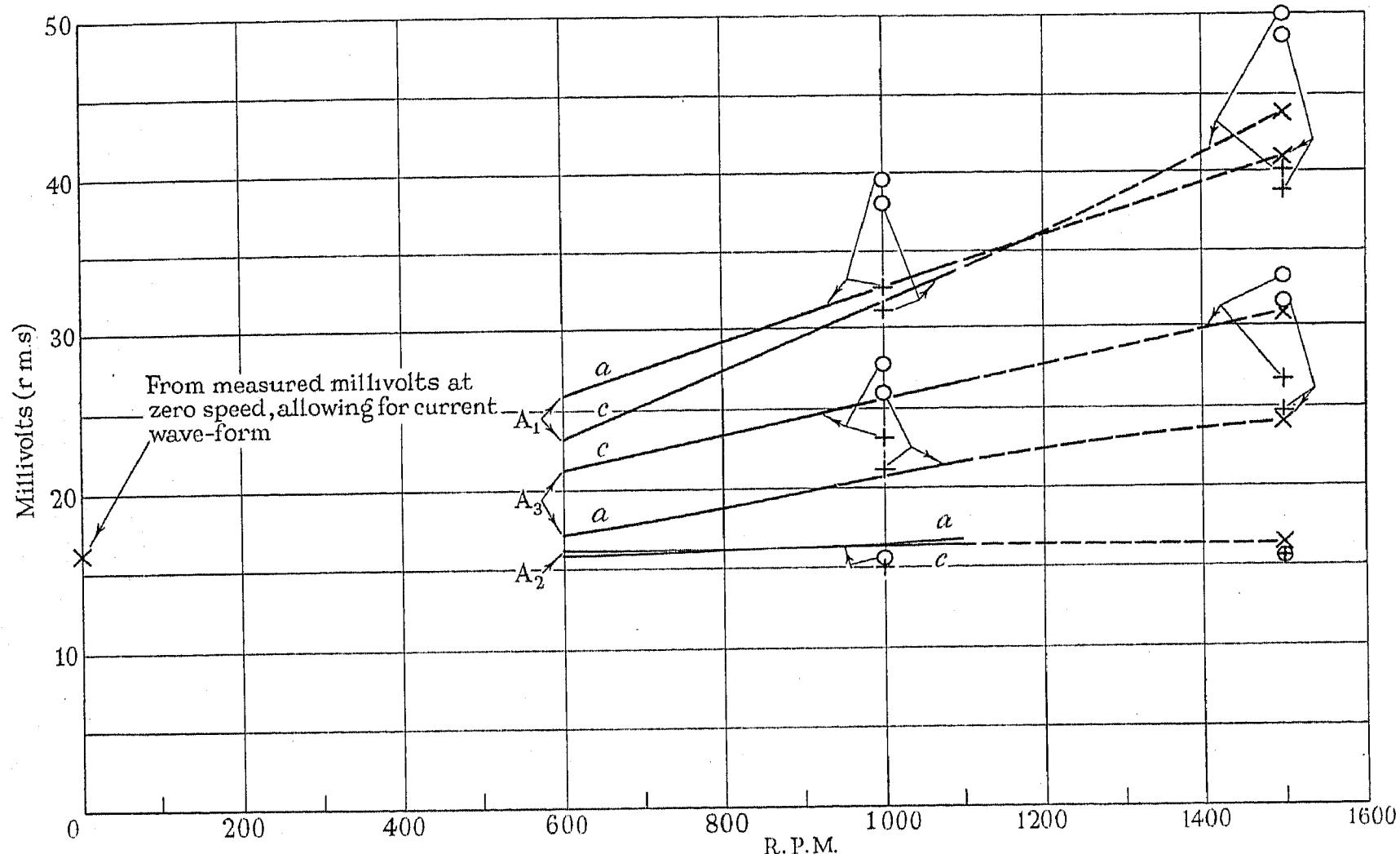
Fig. 16

A₁, A₂, A₃ denote short-circuits at 96 amp., *a* refers to anti-clockwise and *c* to clockwise rotation.
——— and × = results of measurements.
o = calculated result, assuming no " free " portions of search wires.
+ = " reduced ' calculated result(allowing for " free " portions),
for comparison with measurements.

120–300 r.p.m., allowed the change in the current density to be examined in detail throughout the period of slot commutation. Thus the current density began to change, in conductors A and B, as soon as current-change began to take place anywhere in the slot, and the change became more rapid as soon as the current began to change in the conductor itself.

(c) Oscillograms at 1 500 R.P.M., with 40 Amp. in Interpole Windings (No Main Field, No Armature Current)

The interpole flux was observed to cause eddy currents in the conductors. They were of brief duration, and had small peak values. The greatest peak value

flux distribution; the slots are skewed, and the four conductors in series between adjacent connections are not quite in phase, but the error is almost negligible. A selection of tracings of coil voltage on open-circuit, short-circuit, and load, is given in Fig. 19, the curves being drawn in phase. Such wave-shapes are not only of interest, but give clues to the design and performance of the machine. The open-circuit curves show the effect of unequal shunt coils quite clearly.

(e) Open-Circuit Results at 1 000 R.P.M. and Varying Voltage

The general form of the eddy-current wave-shape at a given location was independent of the voltage. The
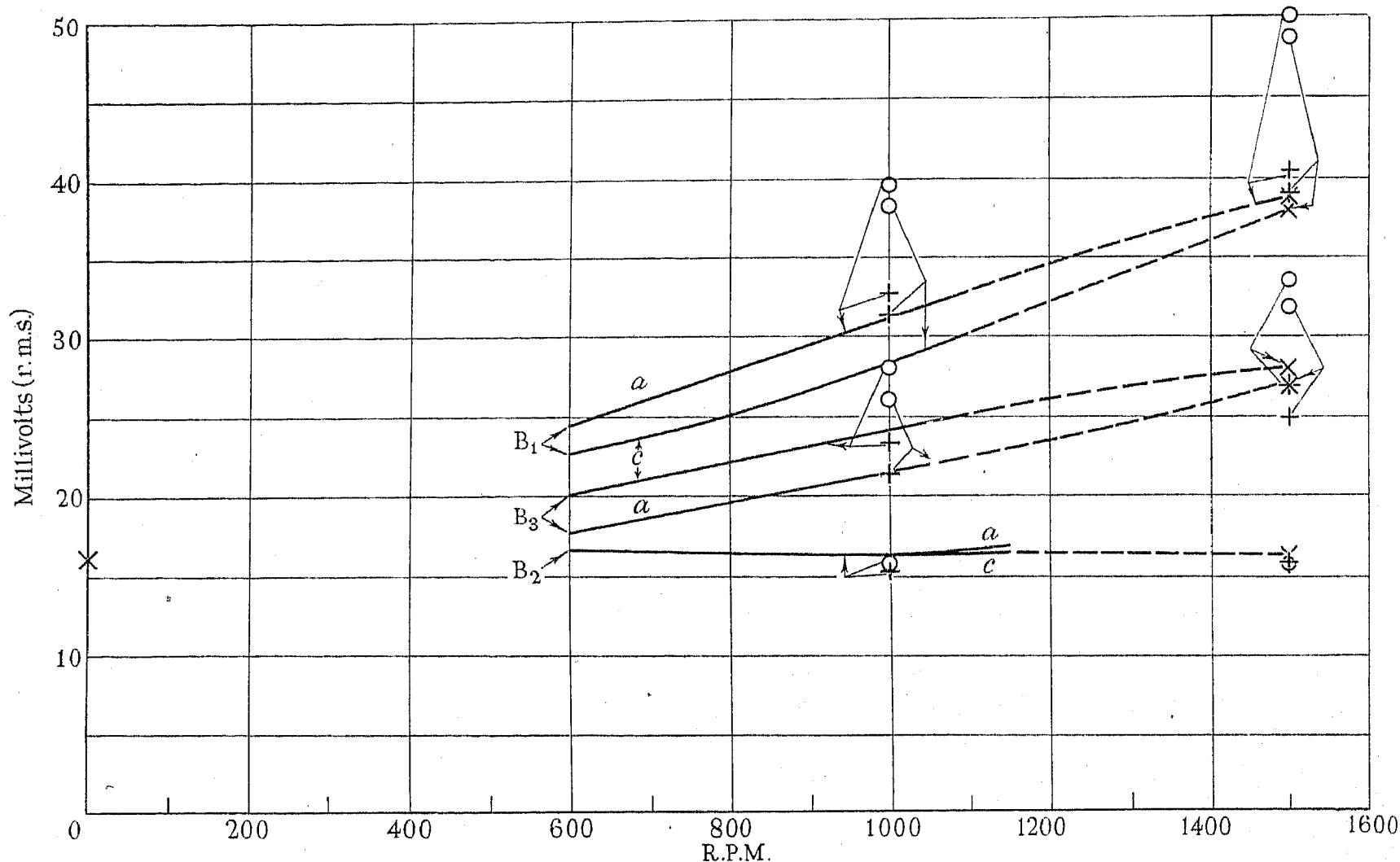
Fig. 17

B_1, B_2, B_3 denote short-circuits at 96 amp.; a refers to anti-clockwise and c to clockwise rotation.
Arrows link calculated and " reduced " calculated values with corresponding measurements; calculated
results based on 16·2 millivolts in search wire at 96 amp., current uniformly distributed.

effect was almost absent from all search wires at voltages below 200 volts, and almost absent at Level 2 in all conditions. At voltages above 500 volts the effect increased rapidly with voltage. In all cases the effects at various levels were comparable in about the degree shown in Figs. 10, 11, and 12.

(f) Load Tests (Motoring) over a Range of Conditions at 1 000 R.P.M.

Some records were made of current-density and coil-voltage wave-forms, at various loadings, and in one case at a low voltage, all at 1 000 r.p.m. The wave-forms show a smooth change from the full-load to the open-circuit condition.

(g) Tests to Justify Provision of Search Wires on Both Sides of the Conductors

The reason for the fitting of search wires in pairs, one on each side of a conductor at a given level to form a short-circuited loop, was primarily an endeavour to allow for slot-flux components due to phase-differences from conductor to conductor across a layer. The tests carried out on single search-wires were not numerous, but led to the view that the double search-wires are essential, to deal with the radial flux in the slot arising from the field. Little evidence was forthcoming of any appreciable effect due to phase-differences between adjacent conductors; effects due to this cause could only occur during the commutation period; at the same time

appreciable effects were observed throughout the period. Fig. 20 shows records made on one pair of search wires. Since the voltage between the two is likely to be due to
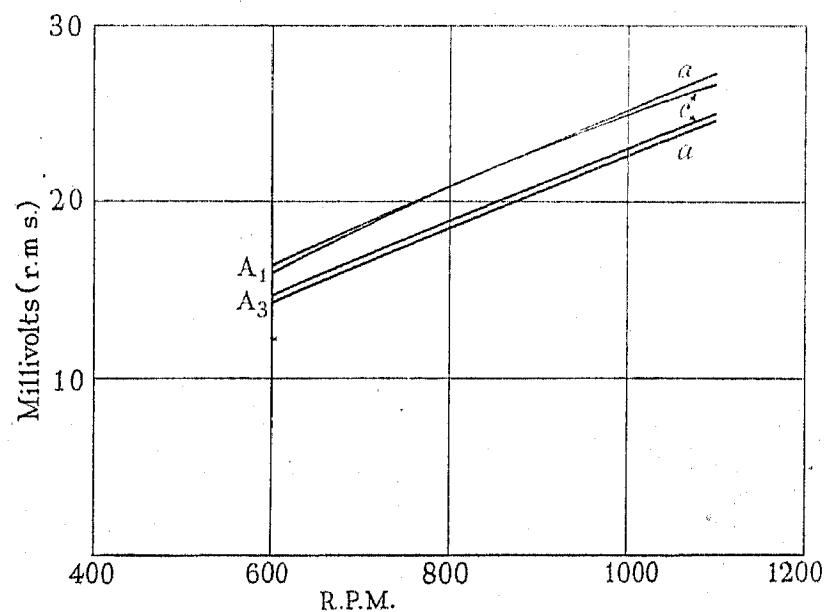
Fig. 18

A_1, A_3 denote open-circuit with field current 2 amp.; a refers to anti-clockwise and c to clockwise rotation. (Results for B are similar and about 10% lower.) Peak tooth density estimated to be 22 300 gauss between banding recesses and 20 000 gauss at the recesses.

variations in flux through the loop constituting the two wires, a differential curve was constructed from the coil-voltage curve (i.e. from the curve of radial flux distri-
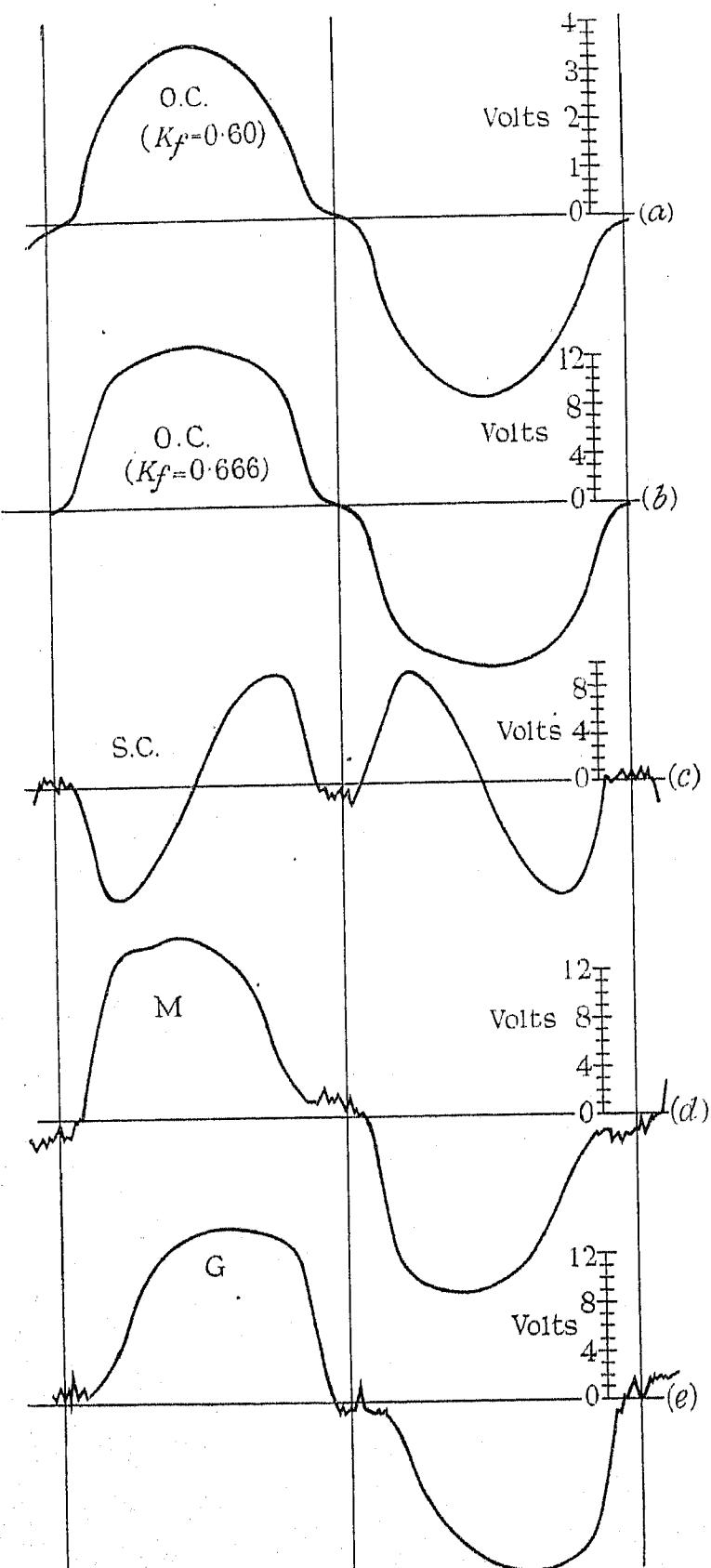
Fig. 19.—Coil-voltage wave-forms under various conditions at 1 000 r.p.m.

(a) 125 volts (scale expanded 4 times).
(b) 500 volts. (Tooth densities corresponding to this and the curves below are given in the Table on page 181.)
(c) 160 amp.
(d) 487 volts, 160 amp. (478 volts from brush to brush).
(e) 487 volts, 128 amp. (492 volts from brush to brush).
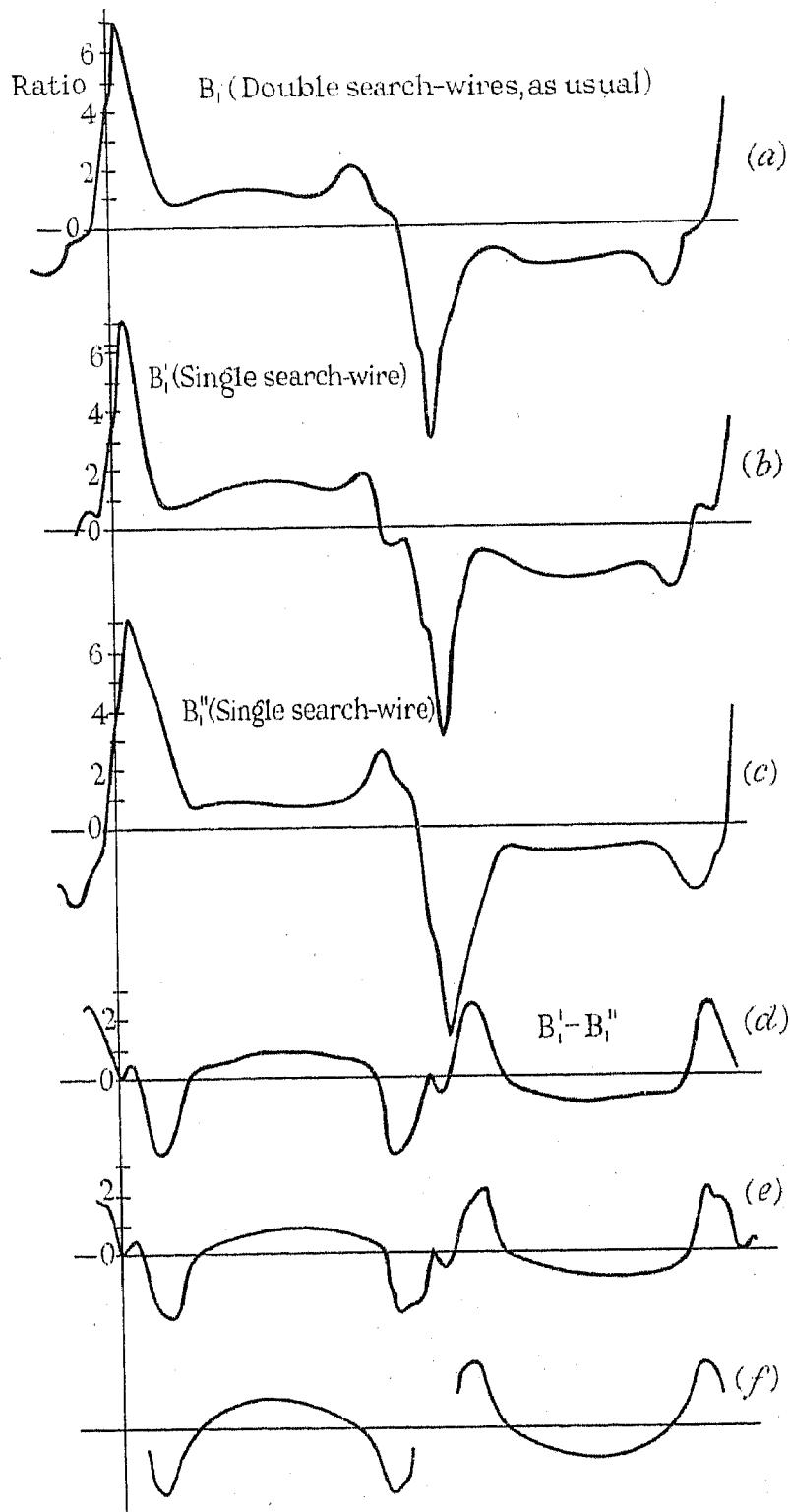
Fig. 20.—Current-density wave-forms in B_1 under short-circuit conditions, using both single and double search-wires.

(d) Difference between the two records made with single search-wire.
(e) Actual oscillograms of voltage in loop formed by the two single search-wires.
(f) First differential of coil-voltage curve (shape as in S.C., Fig. 19): ordinate scale arbitrary.

bution); the similarity between the differential curve and the wave of voltage between B_1' and B_1'' is most marked. It should be noted, however, that the similarity does not extend to the commutation period, where it is not possible to distinguish between e.m.f.'s due to the radial flux of the interpole and e.m.f.'s due to phase-difference between currents.

(h) Load Tests at Low Main Field

A few special tests were made on B_1 with a view to discovering the limiting tooth flux-densities above which an appreciable difference could be discerned between short-circuit results and the corresponding load results. It was found that, at tooth densities up to about 14 000 gauss (apparent),* short-circuit and load results for a given current and speed were indistinguishable. At 1 500 r.p.m. small differences were discernible at a tooth density of 15 600 gauss (apparent).

It may be remarked that the short-circuit tests at 160 amp. gave rise to a reaction field in which the tooth densities reached a peak value of 15 600 gauss (apparent), precisely in regions near the pole-tips where irregularities can be seen in the wave-forms shown in Figs. 7 and 8.

The effect of high tooth densities will be discussed in Section (11), whilst the method of their calculation and a method of estimating the eddy currents due to them is given in Appendix 2.

(11) DISCUSSION OF RESULTS

The earlier paper included curves intended to facilitate the calculation of commutation losses. The results presented in Sections (8) and (9), so far as they are concerned with losses on short-circuit, appear to confirm the theoretical conclusions, within the limits of engineering accuracy. Certain features which are brought out by the theoretical treatment are confirmed in the measurements; such features include the similarity of effects at the centres of conductors in both layers, the difference in the results given by the upper layer according to the direction of rotation,† and the difference in the results obtained at two frequencies. Up to the limits of armature current employed, the r.m.s. values of current density appear to be proportional to the current. It is clear, however, that differences may be accentuated at still higher values of current. Alternatively, it should be recognized that machines of less favourable design (i.e. with no skewing of slots, with smaller air-gaps, with less bevelling of pole-faces, etc.) may give rise to losses different from, and probably greater than, those indicated by theory.

The calculation of commutation losses in the earlier paper was based on the commutation period of individual coils. Such calculations give rise to somewhat higher calculated peaks of current density, and slightly lower conductor losses, than are given by calculations based on the commutation period of the whole layer (assuming all conductors blended into one). This is shown by Figs. 10 and 11 of the earlier paper, where

comparisons may be made of calculations made on the two assumptions (the assumptions would be, for this machine, $n_a = 5$ and $2\beta = 4 \cdot 2°$ in one case, or $n_a = 1$ and $2\beta = 17°$ in the other). The actual state of affairs appears to be a compromise between the two conditions. But in practical cases the difference between the results based on the two assumptions is always small, and certainly smaller than the effects due to other and more obscure causes. It is therefore suggested that the curves given in the earlier paper may be regarded as a sound guide to the losses in the armature windings so far as they are due to the displacement of the conductor current by commutation.

The profound effect of the main field on the wave-shapes of current density is the chief feature of the load results.

The effect appears to be due, in the main, to the magnetic potential-differences which are established across a slot when the gap densities near the adjacent teeth are different. These effects will change as the load changes from full-load (motoring) through open-circuit to full-load (generating). Since the effect is a phenomenon arising out of saturation of iron, the sum of current-density wave-forms on short-circuit and on open-circuit cannot give a wave-form on load. An appreciable difference is to be expected between "generator" wave-forms and "motor" wave-forms, owing to the fact that a conductor experiences the commutation disturbance and then immediately passes through a region in which the densities are either high (for the motoring loads) or low (for the generating loads).

Whilst at first sight the wave-forms of current density on load appear to be beyond explanation, an attempt to forecast the effect of the field does yield results which resemble the measured results in some degree. The calculation is complicated by the skewing of the slots, and by the existence of recesses in the armature for the banding wire. Owing to the complexity of the problem, the steel banding wires are ignored, and the flux distribution in teeth and slots is assumed of simple form (taper ignored); thus an eddy current is calculated, distributed in a simple manner throughout a conductor, so as to be symmetrical about the centre (Level 2).

The method of calculation of the magnetic potential-differences between the ends of a tooth, and of the wave-forms of the eddy current due to these potential differences, is given in Appendix 2.

Fig. 21 shows calculated wave-forms of the eddy currents due to the field, in Level 1 of a conductor, when the field is distributed in the manner shown by the curves of coil-voltage in Fig. 19 for different conditions.*

There is a general similarity between these calculated wave-forms and the experimental wave-forms. The calculated eddy current is about twice the magnitude measured, and considerable detail discrepancies are present; but the results of the crude method of calculation are encouraging. Bearing in mind the discrepancy in the magnitude, mentioned in the preceding sentence, it is possible to imitate the curves shown in Figs. 10 and 11 for the motoring condition by adding three

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* Apparent tooth density is calculated on the assumption of negligible slot flux, and a tooth section equal to the actual section at a level two-thirds of the length from the tip.
† It should be noted that the theory and the measurements show agreement in that there is a much smaller disparity between the r.m.s. density at top and bottom of the conductor in one direction of rotation than in the other.

* The calculated current-densities have been reduced to ratios, in terms of the density due to an undisturbed current of 160 amp. in the armature circuit. It should be noted that the wave-forms for Level 3 calculated on this basis are simply the reversals of the wave-forms for Level 1.

curves; these are the curves M and S.C. of Fig. 21, and a "reduced" calculated curve from Fig. 10; whilst the generating condition can be imitated by reversing (end for end) the wave of eddy current shown for the motoring condition in Fig. 21, and then adding it as before.

One important property of eddy-current wave-forms calculated in this way is that the eddy-current density has a mean value of zero over each half-period. The commutation disturbance has died down in practical cases after a fraction of a half-period, and is thus already of very little account in a generator before any eddy
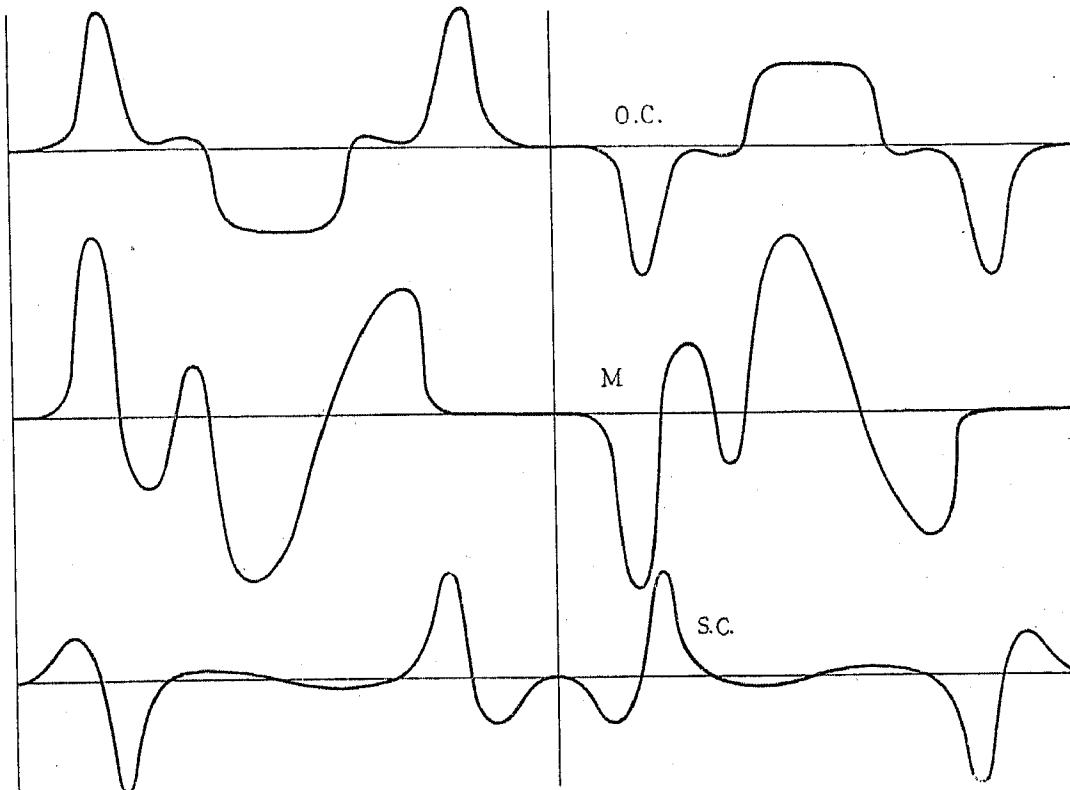
Fig. 21.—Calculated wave-forms of eddy-current density due to the field alone, under the conditions of Figs. 10, 11, and 12.

Main fields for O.C. and M are in phase. Currents for M and S.C. are also in phase, and correspond with phase of currents in Fig. 10.

The current-density wave-forms in the load tests have a sawtooth characteristic. Since the wave-form of the eddy current due to the field is of the nature of a second differential of a curve of tooth ampere-turns, and since this latter curve possesses in an exaggerated degree some of the features of the coil-voltage curve, minute peculiarities of the latter can account for the effects observed. Calculations made from the curves of coil voltage explained the sawtooth characteristics, but the

current due to the field is established. (The case of a motor is not so favourable, in that high tooth-densities occur next to a slot soon after the commutation period of that slot.) It is shown in Appendix 3 that in this case the r.m.s. value of a current-density wave-form on load should be in excess of the r.m.s. value with the same current on short-circuit by an amount which is less than the r.m.s. value of the eddy current due to the field. But the field distribution on load is not the same

Table

Test condition	Gaps (mean axially)	Recesses		Between recesses	
		Gaps	Teeth	Gaps	Teeth
Open-circuit, 500 V, 1 000 r.p.m.	7 830	7 000	18 500	8 170	21 550
Open-circuit, 530 V, 1 000 r.p.m. (condition of Fig. 18)	8 200	7 580	20 000	8 450	22 300
Short-circuit, 160 A, 1 000 r.p.m.	5 360	4 100	10 800	5 900	15 600
Motoring, 160 A, 487 V, 1 000 r.p.m.	8 600	8 200	21 600	8 750	23 100
Generating, 128 A, 487 V, 1 000 r.p.m.	8 300	7 800	20 600	8 550	22 600

small peculiarities themselves were less easily explained. Calculations of field distribution on load did not yield very encouraging results, but it should be noted that bands and banding recesses are present over almost one-third of the core length, and there may be inequalities in the grading of the gaps.

as that on no-load, and the result is known only for the open-circuit condition. At the same time, the results shown in Figs. 13, 14, and 15 suggest that a calculated loss on short-circuit, if added to a known loss due to eddy currents on open-circuit at the appropriate induced voltage, may be expected to give a working value for

the loss on a generating load. (The loss on a motoring load is expected to be somewhat different from that on a generating load, for the same speed, current, and induced e.m.f., owing to the overlapping referred to above; the experimental results seem to show that there is not much difference, and that the losses are slightly less for motoring loads.)

The Table indicates the peak flux-densities estimated to occur in those parts of the armature between banding recesses, and in those parts at the recesses, for the standard conditions applying to Figs. 10 to 15. The tooth densities are " apparent " (i.e. the slot flux in parallel with the tooth flux is ignored), and they are calculated for a level one-third of the length of the tooth away from the root.

(12) TENTATIVE GENERAL CONCLUSIONS

It is concluded that a good engineering approximation to the loss which occurs on load in a d.c. machine may be obtained by the addition of a loss calculated according to the results put forward by the author in the earlier paper, and a loss on open-circuit. (The *calculation* of the open-circuit loss has not been considered.)

The extent to which this conclusion may be generalized is, however, a matter for caution, in view of the extent to which design features may vary from machine to machine. The author believes that machines with small air-gaps, high electric loading of the armature, high tooth flux-densities (i.e. heavy field distortion due to armature reaction, and appreciable slot fluxes due to tooth saturation), may be expected to have high losses due to the field, and total losses not in accordance with these conclusions. The machine which has been the subject of the investigation is of a modern commercial type, free from any unusual features; therefore, these results, together with the design features of the machine, appear to indicate in some measure the criteria which should be observed to produce machines the losses of which can be predicted fairly closely.

There is no reason to suppose that any compromise has to be sought, in the design of a d.c. machine, in regard to losses arising in the armature winding due to commutation and to the field. A machine designed for low (calculated) commutation loss, and low loss in the armature winding on open-circuit, is likely to have a low loss in the winding on load.

(13) ACKNOWLEDGMENTS

APPENDIX 1

Reduction of Calculated Current-Densities, to Allow for Free Portions of Search Wires

The search wires are attached to the armature conductors at points 1·5 in. from the ends of the core. Thus the e.m.f. in a search wire includes that in 3 in. of wire where the conductor is not buried in the iron of the armature. The effect of vent spaces in the core is obscure, and the current disturbance is likely to extend a finite distance along the conductor from the end of the core. It is reasonable to assume undiminished displacement in the vent spaces, and negligible displacement outside the core. On this basis, since the core is 9·625 in. long, the following relation may be stated for any search wire:—

$$\delta'' = 0 \cdot 24\,\delta' + 0 \cdot 76\,\delta$$

where δ is the current-density ratio in the buried portion, and δ'' is the apparent current-density ratio measured from the search-wire voltage; δ' is the current-density ratio due to the undisturbed current, and is unity except during the periods of straight-line commutation.

The full-line calculated curves in Fig. 7 give values of δ. The " reduced " calculated curves give values of δ'', for comparison with the measured voltages.

To find the r.m.s. value of δ'', the relation gives

$$(\delta'')^2 = 0 \cdot 0565(\delta')^2 + 0 \cdot 581(\delta)^2 + 0 \cdot 363(\delta\delta')$$

Hence $(\delta_v'')^2 = 0 \cdot 0565(\delta_v')^2 + 0 \cdot 581(\delta_v)^2 + 0 \cdot 363\,(\delta\delta')_{\text{mean}}$

where δ_v', δ_v'', δ_v are r.m.s. values. The value of δ_v'' is known from the calculations. The value of $(\delta_v')^2$ is given by $\left(1 - \dfrac{4\beta}{3\pi}\right)$, and is $0 \cdot 937$ for $2\beta = 17°.$* The mean value of $\delta\delta'$ for each level can be found from the calculations by adding terms for the 11 harmonics; each such term has the form $\frac{1}{2}a_n b_n \cos\alpha_n$, where a_n is $\dfrac{4}{\pi}\dfrac{\sin n\beta}{n^2\beta}$, and $b_n\underline{/\alpha_n}$ is a vector determined in the course of the calculations.

APPENDIX 2

Calculation of Tooth Ampere-Turns and Eddy-Current Wave-forms arising therefrom

A calibrated record of the voltage wave between adjacent commutator-segments allowed a calculation of mean gap-densities to be made (assuming all four conductors of the two coils in series to be in phase) from the dimensions of the machine. But such mean gap-densities are mean values in the axial direction, and there are regions of high and low density owing to the fact that 29 % of the axial length is occupied by recesses for the banding wire. The resolution of the mean gap-densities into densities at the recesses and between the recesses depends on two assumptions: these are, firstly, a curve of the relation between tooth ampere-turns and the gap density immediately outside the tooth (this was not measured, but was calculated from a curve typical of the sheet steel used for the laminations); and, secondly, that the pole-face and the surface through the roots of

the teeth are magnetic equipotentials.* For each of several gap-dimensions the following calculations were carried out: for an assumed gap-density between recesses, the gap ampere-turns were calculated, and the tooth ampere-turns were read from the tooth curve; the total of the tooth and gap ampere-turns so determined was applied to the regions where the recesses made the gaps larger; this total was subdivided into gap and tooth quantities by a graphical process; the two values of maximum and minimum gap-densities in the axial direction were then converted to a mean value; the whole process was repeated for other assumed maximum

Fig. 22.—Calculation of eddy currents due to the field under the conditions of Figs. 7 and 8.

gap-densities, until finally a graph was obtained connecting the mean density with the maximum and minimum densities. Similar graphs were produced for several gap-lengths. It was thus possible to find the apparent peak densities in the teeth for any test condition.

From a coil-voltage curve and the graphs described above, a curve of the relation between the tooth ampere-turns and the tooth position can be plotted, for the regions at the recesses and between recesses. A mean curve is drawn, and the difference between any two ordinates one slot-pitch apart is assumed to be the potential difference between the sides of the slot, the

centre line of which is midway between the two ordinates. A curve of this potential difference (which is almost identical with the differential of the first curve) is drawn. The differential of this second curve is proportional to the voltage induced at a given level, at a constant velocity.

A rough calculation of the e.m.f.'s at top and bottom of a conductor may be made by assuming the flux across the slot (due to the potential difference) to be uniformly distributed. The e.m.f. actually tends to be greatest near the mouth of the slot; the eddy current established by the simple theory reacts to modify the flux, and tooth taper is an important factor. The calculation of the voltage at the top of a conductor, at a slot velocity of v cm. per sec., yields the following expression for the eddy-current density in amp. per cm²:—

$$\frac{v \times h \times 4\pi}{w_s \times \rho \times 2 \times 10^9} \times \frac{d}{ds}(A.T.)$$

where the eddy current is assumed in phase with the e.m.f., and $\frac{d}{ds}(A.T.)$ is the rate of change of tooth ampere-turns per centimetre movement of the slot. Putting in appropriate values, a differential of 1 ampere-turn per centimetre movement gives $5 \cdot 25$ amp. per cm² at the top and bottom of the conductor.

As an example, Fig. 22 shows the results of the calculation for a short-circuit test at 160 amp. In this and all other cases, the wave-shape of e.m.f. has a mean value of zero over the pole pitch.

APPENDIX 3

The R.M.S. Value of a Current-Density Wave-Form on Load

Let the current-density wave-form due to the armature current and its commutation disturbance be represented by $F(i)$, where values of $F(i)$ are ratios, such as are shown in Figs. 7 and 8. Also let $f(i)$ be the current-density wave-form (also expressed as a ratio with respect to normal current-density) of the eddy current due to the field and the magnetic potential-difference between the sides of a slot. Values of $F(i)$ will approach unity before $f(i)$ has a finite value, in the absence of overlapping. Thus if $f(i)$ is finite over a range of electrical angle θ_1 to θ_2, the contribution to the mean square of $[F(i) + f(i)]$ over the half-period is

$$\frac{1}{\pi}\int_{\theta_1}^{\theta_2}[1 + f(i)]^2 d\theta = \frac{1}{\pi}\int_{\theta_1}^{\theta_2}\{1 + [f(i)]^2 + 2f(i)\}d\theta$$

$$= \frac{\theta_2 - \theta_1}{\pi} + \frac{1}{\pi}\int_{\theta_1}^{\theta_2}[f(i)]^2 d\theta$$

since $\int_{\theta_1}^{\theta_2} f(i)d\theta = 0$, by Appendix 2. Over the whole of the half-period, the mean square of $[F(i) + f(i)]$ is thus the sum of the mean square of $F(i)$ and the mean square of $f(i)$.

Thus, in the absence of overlapping of commutation disturbance and field effect, the r.m.s. value of the current density on load at a given level is the root of

the sum of the squares of the separate r.m.s. values. In this case the r.m.s. value on load might be expected to be between the r.m.s. value on short-circuit and the sum of this short-circuit value and that due to the field alone.

APPENDIX 4

Unexpected Experimental Difficulties

The author hopes that the results presented in this paper will stimulate further investigation, particularly as to losses on load in machines with various well-marked design features. He therefore believes that a short account of unexpected difficulties may well be given here.

(a) Brush position.

The machine was unexpectedly sensitive to brush position, and in the conditions of the tests of Part I it was found that a brush position no more than 2° (electrical) from the correct position caused the machine to develop e.m.f.'s of magnitudes comparable with the low applied voltages. On changing the rotation, the brushes were moved from the correct position for the old rotation by about 3° (electrical) in the new direction of rotation, to obtain the new correct position.* These positions were marked and were used throughout the two programmes. It was found that a neglect to change the brush position on changing rotation was followed by instability, immediately on paralleling for a load test; when a motoring test was arranged for, this instability consisted in a slow increase in the motor load, without any adjustment of field currents being made, immediately after paralleling.

The causes of the need for adjustment of brush position may be (a) a slight rocking of the brushes in their boxes on change of rotation; and (b) a slight surplus strength of the interpoles, with the consequence that the commutation is accelerated and the brush axis is shifted, against the rotation, from the centre of the brush face. Investigation showed that both causes were in operation; it was certain that cause (a) was not very important, since a few minutes' running in the new direction sufficed to establish a stable correct position.

(b) The commutation period of one coil.

The undoubted fact that the commutation period of one coil was always much less than that calculated from the full brush face suggests a need for further investigation. It should be emphasized that the most careful bedding of brush faces, followed by runs at 1 500 r.p.m., failed to have any effect after the first few minutes of running. No record of conductor current ever showed more than about half the calculated commutation period.

* The correct position was taken to be that in which the application of a given suitable low external voltage caused the same current to circulate through the armature circuit whether the armature was running at normal speed or was only crawling.

The effect of the commutation period on the rate of change of the total current in one layer in the slot, and on the radial m.m.f. of that layer [see Section (2) of the earlier paper] is appreciable, and is shown in Fig. 23. The coil commutation period of 4·2° is adopted, in conformity with the second footnote on page 172.

(c) Pick-up wires.

Occasionally, electrical vibrations were recorded which had nothing to do with lubrication, and which consisted
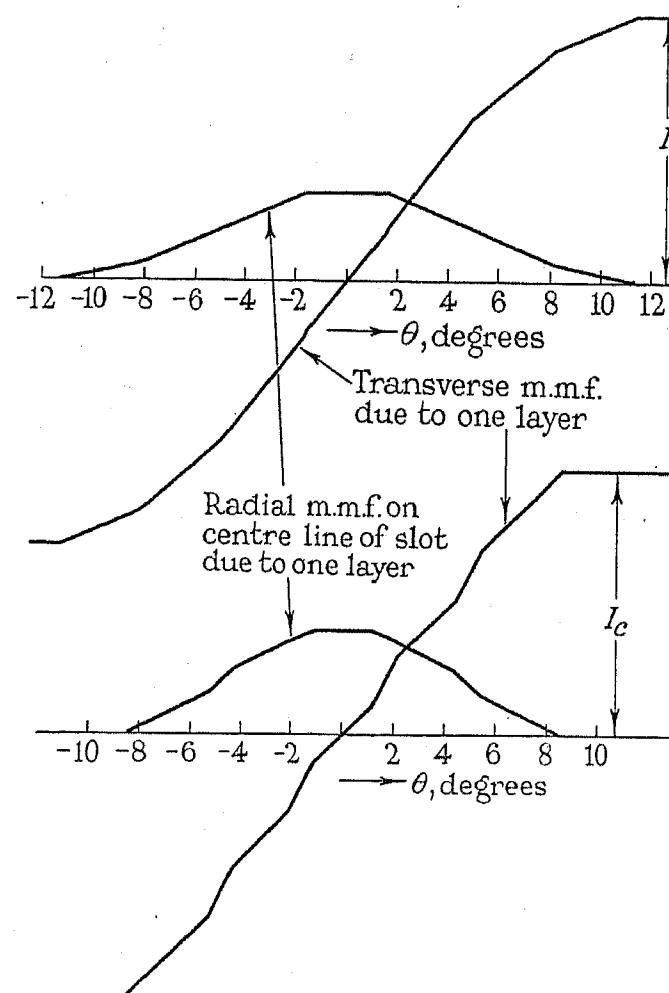

Fig. 23.—Transverse and radial m.m.f.'s in the slot due to one layer, with straight-line commutation.

Upper pair of curves: Commutation period of 1 coil = 9·8° (calculation based on full brush face).

Lower pair of curves: Commutation period of 1 coil = 4·2° (adopted from records).

of very short-period changes of current in the oscillograph element. These changes occurred irregularly, were always over in about one-third of a millisecond, and were always in the direction of decreasing element current. The trouble was never fully explained, but was put down to jumping of the pick-up wire away from the slip-ring. The trouble was more prominent at certain speeds, and was mitigated by fitting damping strips over the group of parallel wires. The use of two grooves in each ring, and double pick-up wires, might have improved the performance.

ELECTRICITY DEMAND AND PRICE*

By D. J. BOLTON, M.Sc., Member.

SUMMARY

It will be generally agreed that demand is just as important a factor as supply in the price-fixing of electricity. The consumer, like the producer, is a free agent, and just as the latter cannot be forced to sell at a loss so the former cannot be compelled to buy at a loss, i.e. to take more than it pays him to do. It is true that the price is actually fixed by the producer, but the consumer has the ultimate veto; and the amount he takes will be governed by the price just as certainly as that price is governed by the cost of production. That being so, it would be expected that all tariff discussions would envisage demand and utility just as much as they do supply and costs. A glance at any engineering index will dispel this idea, and will show at least a hundred entries under the heading of " Costs " for every one under the heading " Demand." Moreover, whilst the term " elasticity of demand " has been employed in tariff discussions, no precise definition appears to have been attempted, still less any appraisal of its value and consequence in electricity supply.

The present paper is devoted almost entirely to the demand aspect and to the effect it has, or should have, upon tariff construction. Part I is a statement of the theory of supply and demand and the price reaction as generally accepted by economists, but interpreted with reference to, and illustrated by, electricity supply. The case of free competition is first dealt with, and then the case of monopoly. Elasticity of demand is explained and defined, and its probable values for various electrical loads are then surmised. This part of the work should not require to be done again.

Part II is an attempt at quantitative application of the theory. Various electrical demand curves are examined and analysed into their component parts. Several methods are tried of plotting and biasing the figures in order to compensate for other variables. Probable elasticity values are estimated, and their bearing on tariff policy is outlined. This part of the paper is a commencement merely, and will be useful rather for its trigger action than for its actual content.

The paper concludes with a short appendix dealing with terms and relationships.

CONTENTS

CONTENTS—*continued*

PART I

GENERAL PRINCIPLES

Dual Aspects

The price of electricity, like the price of anything else, is governed by the twin considerations of supply and demand. There is a certain willingness to supply, based on the cost at which the electricity can be generated and delivered to the consumer's premises; and there is a certain need or demand for electricity, expressed in the figure which consumers are willing to pay. In general, the price which results must reflect and satisfy each set of considerations—both producer and consumer must receive a " fair deal."

These two considerations, of what the service costs to produce and what it is worth to consume, must underlie all tariff construction. On both counts, moreover, electricity supply presents a particularly difficult problem. On the one hand, production costs vary with time and place, and stand in no simple relation to the amount produced. On the other hand, consumption values vary because of the wide range of utilization, and the differing competitive power of the various uses. It seems probable that there must always be a variety of electricity tariffs, differing in kind as well as in size.

Electricity, in fact, is so exceptional that most writers on tariffs have treated it as though it existed *in vacuo,*

and without any assistance from the science of economics. The author believes that in order to understand the exceptions one must know the rules, and that however special a case electricity may be there is always something to be learnt from the general principles of price-fixing. The first step is, therefore, to see how supply and demand normally operate, and how the price of a commodity or service results therefrom.

General Laws of Supply and Demand

These can best be understood in terms of the buying and selling of goods in the market place. The demand for an article is typified by the number of persons desiring it and coming to the market with money in their pockets. The supply is typified by the number of producers of that article coming to the market and willing to sell. It is necessary first to consider a simplified or " ideal " state of things which may be called the condition of pure competition. Such a state exists when there is a standardized product and so many buyers and sellers that the actions of no single one of them have any appreciable effect upon the whole market.

The engineer should be warned that, whilst dignified by the name of " laws," most of the principles here laid down are no more than general tendencies. Although (in the absence of anything else) they can always be expected to operate, they may at any time be upset or obscured by local or special factors. They are the regular tides upon which float a whole fleet of divergent travellers. Moreover, it is rarely possible to isolate a variable and to study the effect of one change at a time. Every " law " enumerated below should therefore be qualified by the proviso " other things being equal "—in practice a well-nigh impossible requirement.

Demand

It is an axiom that people will buy more of an article when it is cheap than when it is dear. Demand goes up as price goes down, and vice versa, i.e. there is an inverse relationship between them. If a curve is plotted connecting the price of an article (ordinates) and the number changing hands (abscissae) the curve will follow the general shape of the line DD′, Fig. 1. At any given price pn the number changing hands will be on, and a price movement up or down will check or stimulate the sales. It is conceivable that in a particular case there might be a simple mathematical relationship between the two quantities, e.g. the number bought might be exactly inversely proportional to the price. The curve would then be a hyperbola, the ends D and D′ being asymptotic to the two axes. Usually the relationship would be a less simple one, and more easily expressed by a curve than by a formula. In any case a continuous rise of the end D means that, however high the price rises, a few articles will be demanded—possibly because of some essential or unique property. But if D meets the y-axis the inference is that at some particular upper price the sales stop entirely, probably because alternatives are obtainable. A curve which continues to infinity at D′ implies an endlessly increasing market as prices go down, whilst one which drops down to meet the x-axis indicates complete saturation. Thus the steepness of the demand

curve may be said to express the necessity or uniqueness of the article, whilst a tendency towards the horizontal implies elasticity and possibilities of substitution.

Although expressed in terms of commodities, the demand curve applies almost equally to all other forms of wealth. It applies to services, to labour, to capital (whose price is the rate of interest), and even to such specialized forms of capital as land.

Supply

In the case of ordinary commodities the law of supply is just the opposite of the law of demand. A rise in price, which would depress demand, has the effect of stimulating supply, whilst a drop in price reduces the supply. A curve of price plotted to a base of quantity supplied slopes upwards as shown at SS′ in Fig. 1. At any given price pn the number offered for sale is on: any lower or higher price will result in a smaller or bigger number being produced and brought to market. The
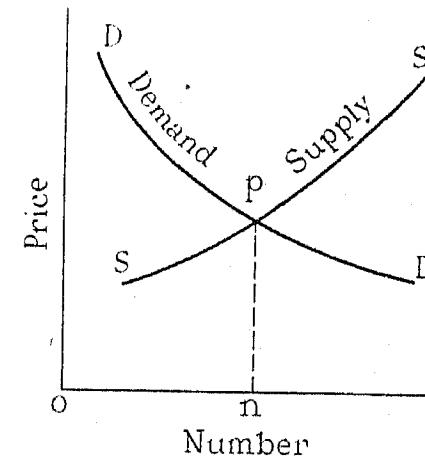

Fig. 1.—Supply and demand.

point p where the demand and supply curves intersect gives the price at which production will exactly balance sales.

The law of supply (as represented by a rising curve of price against quantity) is much less universal than is the law of demand. It applies to freely-produced commodities and services but not necessarily to those of a monopolistic character or those in connection with which there is government action, either central or local. It is only partially applicable to land, capital, and labour.

The time element is important in connection with both the above curves. In general it may be said that time is required for a price-change to achieve its full effect, but this time-lag is usually less with demand than it is with supply. In the case of demand, skilful publicity will greatly assist in lessening the time-lag.

Quantity and Price Reactions

It will be seen from the curves that any change in price has opposite effects on supply and demand. At one particular price pn the two exactly balance, and production equals consumption. If the price rises to a value oh (Fig. 2) there will in due course be a larger quantity os produced and offered for sale. But at this higher price the demand is a smaller quantity od. The result will be a surplus ds, and this will cause the price to fall until the demand overtakes the supply. Thus supply

and demand react on each other, the mechanism of communication being the price. Price is the " cutting edge " of the whole machine, being both the means and the measure of the interaction which takes place.

It is impossible to say where this set of reactions starts or finishes, since it forms an endless chain of processes each of which is both a consequence and a cause. Probably the best starting-point for study is the surplus or deficiency of goods, since this can most easily be visualized. Reverting to our imaginary market, the moment a shortage appears in any commodity the stallkeeper will raise his price, or he will be left without any of that commodity to sell. The higher price will discourage purchasers and stimulate suppliers, and in due course the stallholder will find himself with a surplus, and the price will fall. But owing to the varying time-lags and human reactions the whole process is much more complicated and more uneven than would appear from the above. This chain of mechanism, consisting of surplus or deficiency, price, supply and demand, maintains a precarious balance which it would be flattering to call equilibrium, although it is true that any change sets up forces which tend ultimately to remedy that change (and

Fig. 2.—Price reactions.

usually to produce the opposite change). Rather than use the word " stability " it would be more correct to compare the whole thing to the riding of a bicycle—self-adjusting although in unstable equilibrium—always in the act of falling, yet never (or hardly ever!) suffering a total spill. There would, in fact, appear to be a peculiar appropriateness in the use of the term " trade cycle "!

Factors Composing Supply and Demand

The preceding Sections have treated the operations of demand and supply as though these quantities had an arbitrary existence of their own, instead of being merely the expression of human needs and human productivity. The next step, therefore, is to examine the motive power behind this price machine, and to see how goods come to be demanded and supplied. This involves thinking in terms of people rather than machines, since it is human inclinations that prompt the demand and human disinclinations that limit the supply.

The driving power behind demand is clearly utility, and that behind supply is evidently costs. But a certain difficulty arises here. Price has been described as resulting from the interaction of supply and demand—it is like the handkerchief on the rope in a tug-of-war between two roughly equal teams. But when we look at the motive powers behind the teams no such approximate equality

appears to exist. Price has a very close correlation to costs but it seems to have no correlation whatever to utility. On the contrary, the useful things like bread and water, cotton, and paper, are cheap, whereas the things we can easily do without, such as champagne and silk dresses, are very expensive. It would therefore appear that the symmetrical disposition of supply and demand as equal arbiters in price-fixing breaks down as soon as we look at the underlying factors. Demand can only arise from utility, yet utility seems to have almost no effect upon price.

This difficulty can be explained by means of the conception of " marginal utility." When the housewife decides to buy 6 lb. of bread a week instead of 5 lb. at a total cost of 1s., this does not mean that its utility to her is only represented by 2d. per lb. It means that the utility of the extra loaf is worth that, in comparison with other possible purchases. If she were without bread the utility of a single loaf might be £1, and if the price were that high she might still be willing to pay it. But only when the price comes down to 2d. is it worth her while to buy a sixth loaf. If the baker were able to charge each individual household on a two-part or sliding scale tariff, it would be possible for him to charge heavily on the first loaf; but, under normal conditions of competition, each loaf fetches only the price of the last one. Price is therefore not affected by the mean utility of the whole purchase but only by the marginal utility of the last increment that is just worth purchasing.

It is evident that the marginal utility of a commodity to an individual diminishes with every increase in the amount he has. But what is true of the single purchaser is true of users in the mass; so that, whatever the price, total purchases always approach the saturation value at which the last increment is just worth this much. In the case of luxuries, such as fountain pens, the margin may refer to extra purchases by existing users or to a " marginal purchaser." At a certain price it will just be worth while for a rich man to buy his third pen or a poor man to buy his first.

On the supply side the position is very similar, and somewhat easier to unravel. The dependence of price upon costs is more evident than is the dependence of price upon utility, but even in this case it is not the mean costs but the marginal costs that are important. Since the worst-advantaged producer is presumably making a living, the price must be such as just to pay his costs. Producers who are better placed secure a rent or surplus which may be retained or be " creamed off " by the owners of the plant. (This " economic rent " therefore corresponds to the difference between mean utility and price on the demand curve.) Apart from this rent it will be seen that the height of the supply curve at any point expresses the cost of producing the incremental unit at that point.

Summary for Free Competition

The general laws of supply and demand may now be summed up as follows (expressed, for convenience, in terms of commodities). The price of a commodity tends always to that figure at which supply equals demand, But supply is governed by costs and demand by utility, both these being marginal. Hence a commodity tends

to be produced on a scale at which its marginal cost of production is equal to its marginal utility (each measured in money) and both are equal to its price.   The equation which governs the number of units changing hands can therefore be put into mathematical form as follows:—

Marginal cost = Mean price = Marginal utility. (All these quantities are expressed in pence per unit.)

Monopoly: Supply Curve

Up to this point the treatment has supposed a state of pure competition.   The next step is to consider the effect of a monopoly such as electricity distribution, and its corresponding supply curve.   It will be recalled that the supply curve shows the relationship between the supply price and the number produced.   Its height gives the mean price per unit of all the units supplied (or which tend to be supplied) but is governed by the marginal cost of the last one.   If, in order to increase production from 1 000 to 1 001 units, total costs go up from £100 to £101, the price paid for all units must be high enough to induce this extra production, namely £1 per unit, even though the average cost of all production is only one-tenth of this.

With a freely produced commodity this supply curve is a rising one, since a greater quantity means the coming into operation of inferior land or less efficient plant and undertakings, set in motion by the higher price offered. The price must therefore be sufficient to cover the cost of this incremental production, i.e. it is marginal cost. Better situated land and producers will then earn a rent or surplus.   But under monopoly production there is no open market on the supply side and therefore no supply curve representing the amounts which the producers stand ready to sell at the given prices.   The curves marked " S " in Figs. 3 and 12 represent merely the costs of the one producer, and the height at any point represents his incremental cost.

The cost of an incremental unit in monopolist production such as electricity supply is a somewhat academic conception, since while the annual output in kWh may change in small amounts it is difficult to think of the station size altering by tiny increments.   If, however, one can imagine this to happen, then assuming all the supply characteristics to remain constant (such as load factor and spare-plant proportions) a change in the units supplied will mean a proportional change in every item in the system.   Under these circumstances there is no reason why the incremental cost should be greatly different from the average cost for all the units; although it will probably decline slightly owing to the generally greater economy of large-scale production.   Since the consideration of costs forms no part of the present paper, the simplest likely assumption is best; and, in what follows, the supply curve will be shown as a slightly falling straight line.

Price Under Monopoly

Fig. 3 shows the supply and demand curves (S and D) for a monopoly such as electricity.   The point where they intersect (*p*) is a possible price solution, since it gives a value which would satisfy both parties to the transaction. Under free competition the price would tend to settle at this point, the number sold being *on* at a price *np*.   But

under monopoly supply the producer can fix a higher price than this, and maintain it, since there is no one to undercut him.   He can, in fact, fix any higher price he likes (up to the maximum of *oa*): it is true he will sell less units, but he may make a bigger profit.*

In order to see the economic limits to price-raising under monopoly it is necessary to draw a third line, the incremental-revenue or marginal-revenue curve (I), shown chain-dotted in Fig. 3.   This curve plots the amount added to the total revenue by the sale of each additional unit, and its method of derivation is explained in the Appendix.   Its relationship to the demand curve is given by the fact that for any number of units *om* and price *mq* the area under the I curve (*akmo*) equals the area of the rectangle *bqmo* (= total revenue).
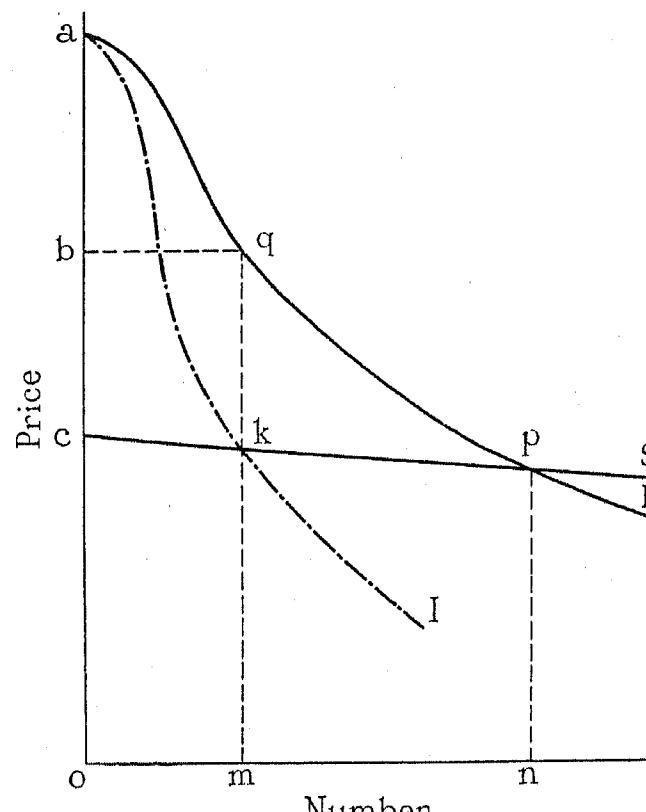

Fig. 3.—Price under monopoly.

If the monopolist wishes to maximize his profits he will fix the price from the intersection of the I and S curves, not the D and S ones (i.e. at the point *q*).   His greatest surplus occurs when the last addition to the revenue just pays the cost of the extra unit sold.   At this point the rates of change of income and expenditure (with reference to the number of units, *N*) are equal and opposite, so that the surplus is a maximum.   On the diagram, the income and expenditure are represented by the areas under the I and S curves respectively, so that the surplus is the area lying between them, i.e. the segment *cka*, which is clearly a maximum at the point shown.

Consider a monopolist supplier who has a free hand in price-fixing, and see what happens as the price is gradually lowered from the maximum of *oa*.   Each successive price-reduction means a bigger sale at a lower price per unit.   So long as the I curve is positive (i.e. for the whole of the portion shown in the Figure) this swells the gross revenue.   From *a* to *q* it swells the net revenue also,

* Since only economic factors are in question ,any legal or other maxima are omitted from consideration.

since gross revenue is increasing faster than costs are increasing. At the point q the profits are a maximum.

From q to p a profit is still being made, but not so much. The demand curve is still above the supply curve, so that the mean revenue per unit is greater than the cost. But the extra units sold in this portion add less to the revenue than they do to the cost, because in order to sell them the price has to be lowered on the existing sales. From the strictly profit-making point of view the expansion qp is therefore not worth while. On the other hand, from the public-utility point of view it *is* worth while: only if the point p is passed will a loss be incurred. (It is understood that the supply curve covers all the essential costs and charges, including interest and repayment at fixed rates. The only item omitted is the fluctuating surplus or profit, e.g. the amount by which the interest on the ordinary shares exceeds the market rate or the rate paid on the debentures.)

In fitting electricity supply into the above framework it must be borne in mind that nearly two-thirds of the field is occupied by local-authority undertakings not working for pecuniary profit. Their chief interest is, or should be, to extend the use of electricity as widely as possible within the limits imposed by running expenses and essential capital charges. The remaining part of the supply is provided by companies, one of whose essential aims is to make a profit. If each type of organization achieves what it sets out to do, there must be some difference in the two results.

The above is a simplification of what is, in fact, highly complicated. The curves are often irregular and only partially known: theoretical generalizations are therefore extremely dangerous. Moreover, personnel counts for much, and many a man will work contrary to rational economic motives through sheer interest in doing a job well. But in spite of all these exceptions and cross-currents it may be said that, granted sufficient economic enlightenment, the general tendency will be for a company to work towards position q and for a public body to work towards p.* In what follows, the former will be referred to as a "profits" basis and the latter as a "costs" basis. A warning must be given against taking these distinctions too rigidly. The points p and q are the two extremes between which actual practice may be expected to range; and they have been defined and labelled in order to clarify the issue rather than to indicate particular operating points.

Strictly speaking, much of the present paper is irrelevant if a purely costs basis is taken. It is then merely a simple question of whether a certain price-reduction is possible, not whether it is worth while. For, provided the cost curve is flat or nearly so, it would seem the duty of the public authority to fix the price at this height, regardless of consequences. The demand curve is then only of interest in telling the authority what load to

expect—it does not affect price-fixing actions in any way. But in practice the position is much less watertight. The load is made up of several groups, each with its particular demand curve, and the incremental costs are difficult to split up rigidly. Hence any allocation of price-reductions between the groups must have regard to their various elasticities, even if a purely costs basis is aimed at. Whether the undertaker is a municipality or a company, the price-fixing action should operate somewhere between p and q, and a knowledge of the two extremes is necessary to both parties.

Two-Part Modification: Summary for Electricity Supply

There is another respect in which the facts are frequently more complicated than the above theory would indicate. It has so far been assumed that all the electricity consumed by any particular group is taken at the same price, i.e. a simple flat-rate tariff is implied. This, however, is the exception rather than the rule, even within a single group, and the next step is to adapt the theory to a multiple tariff. Consider the case in which the tariff is in two parts, a fixed charge of f pence per annum plus a running charge of r pence per kWh. (f will usually vary either with the consumer's demand or with his house size.) The actual consumption must then be split up into two portions, the first block of m units representing the primary or high-yield portion whilst all the remainder forms the secondary or follow-on portion. Payment for the primary portion, including the service or convenience of having electricity for some particular purpose, is covered by a price of $\{(f/m) + r\}$ pence per unit, whilst the subsequent units are priced at r pence per unit. (A block rate or sliding-scale tariff, particularly if it has only two blocks, can obviously be fitted into the same framework.)

On the principles here outlined, the price ruling in the first block $\{(f/m) + r\}$ cannot be higher than the marginal utility of the block, i.e. the usefulness (valued in pence) of the last unit consumed in that block. It must not be lower than the marginal cost of the same, i.e. the cost of supplying the last unit; and it may be anywhere in between, according to the aims and constitution of the authority. Exactly the same remarks apply to the price of the second block (r).

Provided the loads and prices can be sectionalized in this way, these principles will be found of general application to electricity tariffs. The price for any section of load must not be lower than the incremental cost and cannot be higher than the incremental utility of the particular service or market which it is desired to fill. (The word "cannot" means that if the price is fixed any higher the last unit will not be purchased.) Nor is it necessary to have the complete range of figures. Provided portions of the supply (incremental cost) and demand (incremental utility) curves for each load section are known round about the working point, the price can be fixed—either where these curves cross or somewhat higher.

Another important practical conclusion which emerges is the absolute necessity for multiple tariffs. If all units are sold at the same price this cannot be higher than the

* It might be thought that a simple check on this would be to compare the mean prices charged by companies and by local authorities respectively. Apart, however, from the different character of the areas they usually serve, there are a number of other complicating factors. For example, the amounts put in by depreciation reserves, loan repayment, etc., are considerably higher in the case of municipal undertakings, and this alone would be sufficient to level-up present prices though it might accentuate future ones. Moreover, even the company undertakings, although their *raison d'être* is, of course, to make profits, acknowledge certain responsibilities as public utilities and do not necessarily operate merely as commercial enterprises. Meanwhile, the Electricity Commissioners take a paternal interest in the whole field and can intervene in cases where the price seems excessive.

utility of the last unit sold.   Mean prices will be governed by marginal utility.   But subsequent results will show that when the load is sectionalized the various demand curves prove to be quite different, so that a price which approaches saturation on one curve is throttling another. If we are to sell, say, 1 000 units a year to a householder at a single flat rate, this must be no higher than the utility to him of the thousandth unit.   If the price was a penny it would not be enough that the total value of his electricity should be 1 000d. or £4 3s. 4d. a year.   At such a rate he might be very glad indeed to satisfy his more urgent requirements, but before he will plug in a bedroom fire which will bring up his consumption from 900 to 1 000 units he must be satisfied that the extra comfort is worth the extra 8s. 4d.   The only way to " cash in " on the superior utility of the first batch of units is to charge more for them, and then to bring down the follow-on rate to the level of the lowest yield of any unit sold.

Importance of Demand

It is necessary at this point to turn aside from the strict science of the subject and engage in a little polemic. The fundamental assumption of this paper—that, in tariff construction, demand must be considered as well as supply—is frequently attacked, and a few words must be spoken in its defence.   It has been seen above that the monopolist purveyor of a service is very different from a commodity manufacturer working in a free market.   He is by way of being a dictator, and can fix the price very much where he chooses.   It is sometimes argued that under these circumstances the only safe guide is his own particular costs; and that he has no business to consider the demand aspect at all or to take into account " what the market will bear."   So prevalent is this idea that it has become almost unconscious, and indeed a part of the language of the subject.   People frequently speak of an " accurate " tariff; meaning, of course, a tariff which accurately represents costs, not one which accurately represents value to the consumer.   The very use of an exact and absolute word like " accurate " in connection with such a tug-of-war matter as price-fixing is evidence of the underlying and unquestioned assumption that the only function of a tariff is to represent costs.

Taken by and large, no doubt the assumption is a sound one.   The undertaking as a whole should pay its way, and on the other hand it should not " exploit " its privileged position.   But this is far from saying that it is the business of each separate tariff to recover the costs on that particular portion of load, quite oblivious of what service it is rendering to the user.   Whatever its peculiarities, electricity supply is a sale like any other sale, and the business of a tariff is to satisfy both parties to the transaction.   The buyer will be satisfied if he obtains value for money, i.e. a gratification which he cannot obtain more cheaply by any alternative service.   The seller will be satisfied if on the whole his costs are covered with the required margin of profit.   The railways do not charge as much for carrying 1 cwt. of coal as they do for carrying 1 cwt. of gold, although since the former is the bulkier they might reasonably charge more for it.   The hundredweight of refined gold is like the 50 watt of refined power that works our wireless set or our electric clocks, whilst the coal is like the heating energy of which

so much more is required to produce an effective result. It may not always be feasible to employ differential rates, but it is certainly always justifiable.

Apart altogether from any cost justification of differential rates, the burden of the present paper is that demand must be taken into consideration because it governs the reaction just as fully as supply does.   The seller of a monopolist article or service is, in fact, by no means a dictator standing above the law, but is just as rigidly controlled by the curve intersections as is the buyer.   Though the seller fixes the price, the buyer fixes the quantity that shall be bought at that price, and a knowledge of his reactions is essential to the proper conduct of the seller's undertaking.

Moreover, if one surveys the actual tariffs, one finds that demand has left its imprint just as certainly as supply has done.   The differences in character between industrial and domestic tariffs or the differences in size between lighting and heating rates cannot possibly be explained on cost grounds, and all attempts to do so are the sheerest casuistry.   But whereas costs are openly consulted, the influence of demand has been largely unconscious, or at least shamefaced.   One object of the present paper is to bring these suppressed motives up to the surface of consciousness and to rationalize them into a scientific working hypothesis.

Necessity and Luxury Demands: Elasticity

Before applying the above theory quantitatively to the case of electricity supply it will be well to study the demand curves again.   This will be done in terms of goods, but it should be stated that, in matters of demand, precisely the same laws apply to services, capital, and land as to ordinary commodities.   The first step in this study is to distinguish between necessities and luxuries, although it must not be forgotten that these are relative terms.

Necessities are those goods (or services) which are urgently needed by large numbers of people, but usually only in strictly limited quantities.   Thus food and clothing in certain amounts are essential to each individual, but no one needs (and very few would want) large quantities of meals or clothes at any one time.   The demand curve is then a very steep one, as shown in Fig. 4.   Even a high price will not deter people from buying their irreducible minimum, and conversely even a very low price will not tempt them to buy in much larger quantities. Since the whole population is presumed to be already buying the article in question there is no new market to draw upon, so that what is true of the individual applies also to the sales as a whole.

Luxuries are those goods or services which can easily be forgone, and in fact are forgone by large numbers of people, even by those who desire them.   It follows that if the price of a luxury article goes down, the sales are likely to go up very considerably, since there are large numbers of potential users to draw upon.   The demand curve in this case is relatively flat, as shown in Fig. 4, since a decrease in price causes a large sales increase whilst a rise in price may put the article almost out of the market.

Even within a single class of commodity, such as foodstuffs, it is evident that there are, relatively speaking,

both necessities (e.g. bread) and luxuries (e.g. fowl and turbot). If the price of bread went up the sales would be only moderately reduced, whilst if the price fell to one-half or even one-tenth the increase in consumption would not be enormous. But if the price of chicken were to fall in this ratio there would be many times as much consumed as there is at present.

It is usual to employ the word " elasticity " to denote the quality possessed by the flat curve. Elasticity could be defined as the percentage increase in sales resulting from a 1 % drop in price. Alternatively it might be defined as the degree of flatness, or the reciprocal of the slope (dx/dy), of the demand curve.* It will be seen that elasticity is characteristic of luxury articles, and rigidity or inelasticity of necessities.†

Before leaving the subject it will be well to tabulate the various causes of sales elasticity, all of which will be found to be strictly relevant to electricity supply. When the price goes up, consumption may go down through
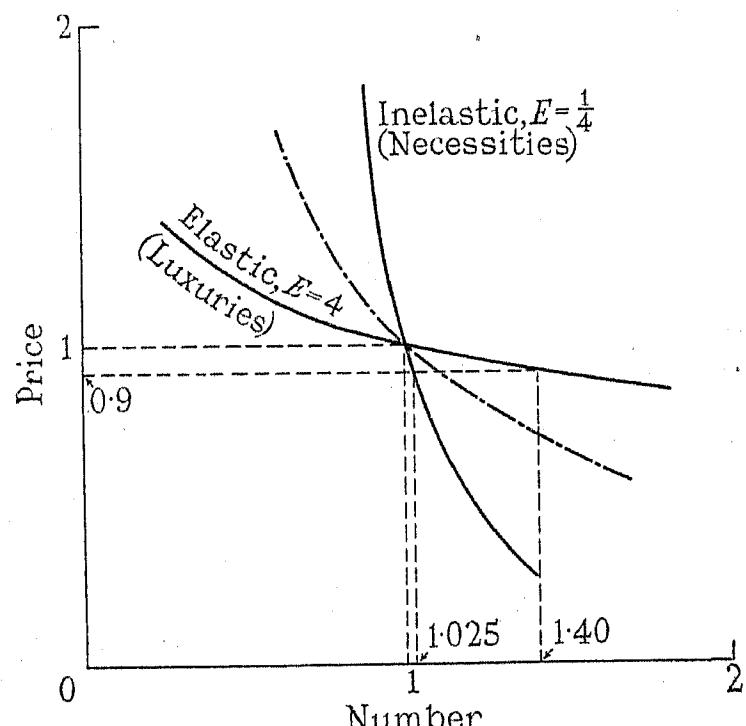
Fig. 4.—Demand curves.

(a) abstinence, (b) use of substitutes, (c) individual production. Thus if the price of a service such as electric light goes up, one may use less light, one may use other illuminants, or one may generate for oneself. Conversely, when the price goes down it is possible (i) to use more in the original capacity, and (ii) to develop other uses. Anything tending to make any of the above easier will increase the elasticity of the demand and the flatness of the curve.

There is a further distinction which may be made. Except in the case of absolute necessities there are two distinct channels through which elasticity may operate, no matter which of the above causes it is due to. It may operate either through additional consumption by existing consumers or through the connection of fresh

consumers. For some purposes it may be convenient to distinguish between these two methods, and with electricity supply it is a simple matter to do so. Curves plotted to a base of units per consumer show the former, whilst those giving the number of consumers per head of population show the latter. The overall elasticity shown by the units per head is the resultant of the two.

Price-Fixing of Necessities and Luxuries

In the discussion on price reactions under free competition it was implied that the price goes up or down automatically as a shortage or a surplus reveals itself. But in almost all cases the actual price-fixing is done deliberately by the producer, although it is true that in the case of freely-produced commodities this balance of stock does furnish the motive power for price-changes. Since the producer naturally tries to get the highest price he can, it will be well to consider just what limits this price-raising.

A rise in price normally produces two effects, both tending to check this rise, namely a reduction in consumption and an increase in production. But in the case of necessities the former element is barely present, and only the latter is operative. Referring again to Fig. 4, the demand curve for an absolute necessity is almost vertical so that a price-change hardly affects the sales, and a rise in price cannot be relied upon (on the demand side) to produce a surplus. Furthermore, when there is any check upon free production, and still more when there is a monopoly, the supply curve also fails to operate, and a rise in price cannot be relied upon (on the supply side) to stimulate production and produce a surplus. A private monopoly in an essential article or service is therefore deprived of both the natural checks on price-raising.

It follows that the monopoly of supply in a necessary service forms a very powerful weapon for ill or good. In private hands it tends inevitably to abuse unless checked by strict external control. In disinterested hands and wisely directed it can be an effective instrument of public service. For when both necessity and luxury consumption are comprised in a single supply, it will often be possible to overcharge on the necessity consumption and use the proceeds so as to undercharge on the luxury consumption; thus developing the latter without materially damaging the former.

The above can be more precisely studied from the curve and theory of Fig. 3. Under free competition the price is not determined by any one producer, and it tends to gravitate to the position p. But the monopolist can fix it at any higher figure he chooses, and up to the point q there is an actual inducement for him to do so. Now the difference between q and p is fixed by the difference between the mean-revenue or demand curve (continuous line) and the incremental-revenue curve (chain-dotted line). This difference will become greater the steeper the demand curve (for an exact proof of this see Appendix). Conversely, with a horizontal demand curve the two lines coalesce. Hence the steeper the demand curve and the more necessary or unique the article the greater is the power and risk of monopoly supply.

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* These two definitions are not identical, as will be explained later.
† Warning should again be given that all these terms—luxury, elasticity, and the like—denote relative and not absolute quantities. The demand curve is never completely vertical or completely flat—there are always alternatives and substitutes. It is easy to quote extreme cases, but most articles occupy some intermediate position in the chain which ranges from loaves to lipstick or from a water supply to a valeting service. And it is a commonplace that the luxuries of one age become the necessities of the next.

Mathematics of Elasticity

It now becomes necessary to define elasticity in more precise terms. If we are speaking of any one point such as that where the curves cross in Fig. 4, there is no doubt as to what is meant—a small slope indicates a big change in sales for a given change in price, and vice versa. This change may be denoted by the general term " response "—the two thick lines then indicate big and small responses to price-change, while the chain-dotted line shows a moderate response. But the demand curves are rarely straight: frequently they bend in an asymptotic manner as they approach the axes, and in other cases they bend into one or other of the axes.

The total response (or reversed slope) may therefore be analysed into two component elements, one due to the character of the demand curve as a whole and the other due to the particular position on the curve. As far as possible the word " elasticity " will be reserved for the former and more important quality, though the distinction between the two is not always easy to observe. Thus some articles are essentially necessities or luxuries, whilst others may be a necessity in small quantities and a luxury in large. The latter is usually because there are several distinct uses, as when water is used in small quantities for drinking and in large quantities for flower-watering or car-spraying. (The word " saturation," referring particularly to inelasticity at the right-hand end of the curve, is a less precise and therefore less satisfactory one.)

If the y and x variables of the demand curve are denoted by P (price per unit) and N (number of units) respectively, then the total response of the curve is the rate-of-change of numbers with price, i.e. the reciprocal of the slope dN/dP. But the elasticity is the *proportional* change of numbers with price, or $\delta N/N$ divided by $\delta P/P$. A criterion of elasticity can then be established as follows: If at all points in the demand curve the quantity sold is inversely proportional to the price ($N \propto 1/P$), i.e. if the curve is a rectangular hyperbola, the elasticity is uniform throughout and may be regarded as unity. The aggregate of expenditure on the commodity (= Price per article × Number of articles) is then a constant. Such a curve is shown chain-dotted in Fig. 4.

To test the elasticity of a demand curve at any point, the method therefore is to draw a portion of the rectangular hyperbola through that point, and see whether the demand curve is steeper or less steep than the hyperbola (elasticity less or more than unity). In words, if a larger total amount is spent on a thing when its price is low than when its price is high (curve less steep than hyperbola) the demand may be said to be elastic, and if a smaller amount, inelastic. If the curve is horizontal anywhere, the elasticity at that point is infinity, and if vertical it is zero. Unit elasticity occurs when a 1 % drop in price gives a 1 % increase in sales so that the total revenue is unaltered.

It will be seen that the above description of elasticity refers not to the total response or slope of the curve but to its percentage slope. The elasticity may then be precisely defined as the limiting value (when the changes are made infinitely small) of the ratio of the proportional change in sales to the proportional change in price, or $\delta N/N$ divided by $\delta P/P$, where N and P denote the number

and price respectively. But since an increase in price brings a decrease in sales it is necessary to insert a negative sign; thus the elasticity is given by

$$E = L - \frac{\delta N}{N} \times \frac{P}{\delta P} = -\frac{dN}{dP} \times \frac{P}{N}$$

When the total revenue is a constant,

$$NP = \text{constant} = C, \quad \text{or} \quad N = \frac{C}{P}$$

and

$$\frac{dN}{dP} = -\frac{C}{P^2}$$

The elasticity, from the above formula, is then given by

$$E = -\frac{dN}{dP} \times \frac{P}{N} = \frac{C}{P^2} \times \frac{P}{N} = \frac{C}{PN} = 1$$

It will therefore be seen that the formula agrees with the description in that it gives an elasticity value of unity for the case described.

It is easy to find examples of the above in electricity supply, particularly in the domestic sphere. Electrical consumption clearly exhibits both elements of response change, namely that due to position on the curve and that due to the character of the curve as a whole. As regards position, it might be found that at one price a 1 % drop in the heating rate produced a 3 % increase in the consumption, whilst at some lower point it produced only a 2 % increase (or in another case, 4 %). The smaller increase might indicate some approach to relative saturation either in the use by existing consumers or in the connection of fresh ones. The higher increase might indicate that a very favourable competitive price (*vis-à-vis* alternative supplies) was being reached.

Comparing curves as a whole, a drop in the price for purely lighting supplies would almost certainly reduce the revenue from existing consumers, and probably reduce the total lighting revenue unless the district was quite undeveloped. A 1 % fall in price at any point in the lighting curve might then increase the sales by only $\frac{1}{2}$ %, whilst throughout the heating-load curve the corresponding figure might never be less than 2. (The continuous lines in Fig. 4 are portions of the curves plotting elasticities of 4 and $\frac{1}{4}$ respectively. A 10 % drop in price—shown by the dotted lines—increases the sales by approximately 40 % on one curve and $2\frac{1}{2}$ % on the other.)

It is worth noting that all these sales-changes, particularly the increases which follow from price reductions, are not immediate and automatic: their full effect only comes as the result of time and publicity.

Electricity Uses and Demand

The above general remarks regarding demand characteristics may usefully be amplified in the case of electricity. Owing to the wide range of uses, the demand curve may be anything from the very steep to the very flat, since electricity is a necessity for some purposes and a luxury for others. For wireless reception, metal plating, vacuum cleaning, etc., electricity is unique, and the same is now almost true of lighting. Such a demand is inelastic, and, however high the price, one must either pay it or generate for oneself. Conversely, if the price is

reduced, the vacuum cleaner or the wireless set will not necessarily be used any more than they were, nor will the lamps be always left burning. A fall in the price of electricity for purposes such as the above will produce comparatively little increase in load. Very few present users would double their lighting consumption if the price of electricity were suddenly halved, and the same applies even more to the use of such things as cleaners and refrigerators. It is true that in order to get the overall elasticity one must add to the elasticity of existing consumers the elasticity of new connections. But the growth in connections depends on the proportion of unwired houses in cabled streets, the cost of and facilities for wiring, and so many other factors besides the price of energy that the elasticity on this score is not likely to be very great. Even allowing for this, it is probable that a drop in price to one-half would not increase the lighting load by more than 20 % to 30 %.

Compare all this with the consumption of electricity, again in the home, for room heating, cooking, or water heating. In each case there is an alternative, not so good perhaps, but good nevertheless. Electricity still has its peculiar merits, worth much, but hardly priceless; and unless the tariff is low the cheaper alternatives are likely to prevail. Such a load is extremely responsive and elastic, and under these circumstances a reduction in price to one-half might increase the consumption by several hundreds per cent.

Power loads lie somewhere between the two extremes just mentioned, since they are more closely competitive (and therefore more elastic) than lighting loads, but less so than heating loads. Electric power from the mains is usually very much better and cheaper than anything else available (particularly to the small-scale user), but not overwhelmingly so. Electricity, then, is valuable but not indispensable, and the demand curve has an intermediate slope. The magnitude as well as the type of use is important here, and a price which will satisfy a baker for driving his dough-mixer will not tempt him for heating his oven, nor will it secure the power load of the large industrialist. Another special feature of the power-load elasticity is that the time-lag is much greater than with the domestic load, since the total power requirements are almost unaffected by the cost of energy, whilst the change-over from other drives takes time to effect.

The following is a list of uses of electricity, roughly in the order of their rigidity of demand, itself a measure of their competing power with the alternatives available. In all cases there is the alternative of private generation, which becomes more feasible the larger the size.

Small specialized uses: timekeeping, wireless reception, small-scale communications, plating, battery-charging, etc.

Very small power: vacuum cleaners, grinders, drills, slicers, etc.

Lighting.

Medium and large power: industrial, traction, etc.

Heating.

The value to an individual of the various services could be roughly assessed by supposing the energy price to be gradually lowered in the manner of a Dutch auction. A typical householder, for example, might decide that electricity was just worth while at 1s. a unit for operating a wireless set, that it was just worth 8d. a unit for vacuum cleaning, 6d. a unit for lighting, 1d. for cooking, and so on. It will be noted again that the size as well as the purpose of the application is an important element in demand elasticity. When very small amounts of power are required, as in refrigerators and washing machines, the cost of the apparatus is usually the determining factor, and the price of energy hardly affects the use at all.

Without unduly anticipating what follows, the moral of the above may be briefly pointed out. The more nearly essential and unique the services conferred by electricity the higher and steeper will be the demand curve and the higher should be the price (so far as this is allowed to be governed by demand). When the service rendered is a strictly competitive one the price must be so too, since the load will then be sensitively dependent upon the tariff figures. When both sorts of consumption occur within a single household or factory, the situation can be met either by separate metering or by a fixed charge corresponding to the rigid portion of the consumption.

PART II
ELECTRICITY DATA AND APPLICATIONS
Demand Curve Analysis

So far, the paper has confined itself to the general theory of supply and demand, and the only electrical references have been either hypothetical values to illustrate the theory or else *a priori* arguments as to what might reasonably be expected to happen. The next step is to obtain some quantitative statements of electricity demand, capable of giving numerical values to the tariff construction. Evidently, if there is to be any useful application of the theory, there must in the first place be a solid basis of data on which to work. Plenty of work has been done on the supply curve, and most managers of electricity undertakings when confronted with a potential addition to their load could make a fair estimate of its incremental cost, provided they had full information as to its position, peak incidence, etc. What they would not find so easy is to say what load would follow from a given price-reduction. Nothing more will therefore be said regarding the supply curve, and what follows refers entirely to demand.

The chief difficulty in obtaining suitable data is the difficulty common to all economic problems, that of isolating the different variables. Consider first the question of differences of use. The chief groups recognized by the Electricity Commissioners are the industrial and the domestic, which between them account for over 90 % of both units and revenue. The actual figures are given in Table 1, whilst Fig. 5 shows the results graphically and including also the other two small groups.

The industrial group is relatively uniform and homogeneous: the electricity is chiefly put to one purpose, namely power production, and the competitive differences within the group are a function of size rather than of kind. The domestic group includes a much greater variety of uses which compete at a number of very different price-levels. The utmost differentiation that one can hope to achieve is to split the domestic consumption into two portions, the high-yield or necessity portion comprising

lighting, cleaning, wireless, etc., and the low-yield or luxury portion comprising heating and cooking. Lighting is the type and forms the bulk of this first portion,

Table 1

PERCENTAGE OF TOTAL SALES

	Units	Revenue
Industrial ..	54·8	32·1
Domestic ..	36·6	62·5
Sum	91·4	94·6

and when there are separate tariffs it is frequently the only use included. It will therefore be convenient to use the words " lighting " and " heating " to indicate the two portions.

single year must be taken and a number of undertakings compared together; either by means of a " target " diagram or else by sorting them into a number of different price-groups. In comparing undertakings there may be other important variables, e.g. on the domestic side the wealth or poverty of the area and the availability and price of alternatives such as gas, and on the power side the degree of industrialization. Only by comparing a very large number together can these other differences be eliminated, and even this is hardly possible with the power load. Finally, when it appears that the analysis is complete, and a " pure " single-use demand curve emerges free from all disturbing factors, it may still be desirable to split this up into its two ultimate components —units per consumer and consumers per head of population.

It will be seen that the correspondence between consumption and price illustrated in an overall curve such as that of Fig. 6 proves on analysis to be the composite result of some half-dozen variables, and it is extremely difficult to separate all these out. As a result there is
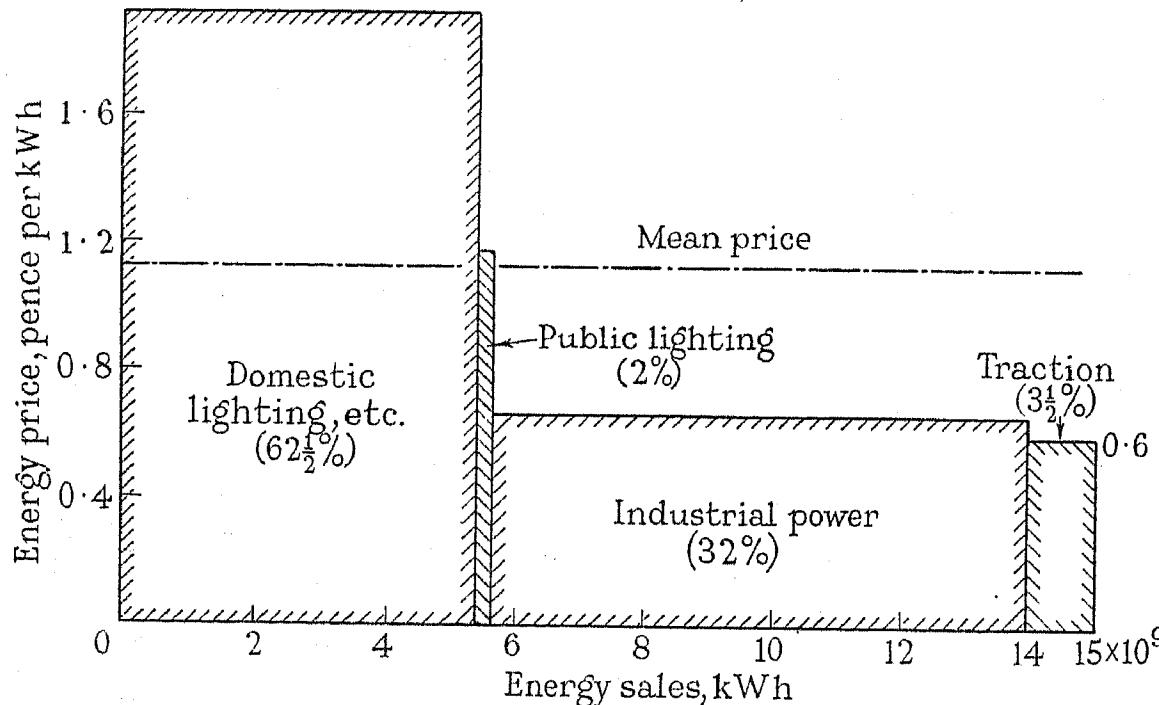
Fig. 5.—Sales of authorized undertakings, 1935–36.
Areas indicate revenue.   Figures in brackets indicate percentage of total revenue.

These two components of the domestic demand can only be separately studied by considering those undertakings which have separate flat rates for the two, and which have no alternative " all-in " tariff. But there are not sufficient of such undertakings to furnish enough price-variations at any one moment. It is therefore necessary to take a single undertaking and to trace its progress over a sufficient period to include a number of price-charges: this involves another variable, namely time. The effect of time on the demand response can be studied by plotting the figures, either for single undertakings or for aggregates, over a number of years. If in this period there have been other important alterations, such as a change in the general price-level or in the population served, it may be necessary to bias the figures so as to eliminate these other changes.

When it is desired to eliminate the time element, a

no one satisfactory basis of comparison, and the best plan is to take shots from a number of different angles in turn, hoping to cancel out their respective faults.

Weir Curve

In Fig. 6 is reproduced what may be called the classic of electricity demand curves, namely that supplied by Mr. J. M. Kennedy to the Weir Committee and printed in their Report of 1926. It plots average price obtained, against units sold per head of population, and is a smooth curve representing the general trend of a number of scattered points, one for each undertaking. (It should be stated that in the original these points were shown, whilst the additional curves mentioned below were not shown.) Through the centre point is drawn the chain-dotted hyperbola of unit elasticity (constant total revenue), and since the demand curve is generally steeper

than this hyperbola it may be inferred that the demand for electricity is, in general, elastic.

The above evidently does not take us very far. Not only does the curve embody without discrimination all the variables which have been mentioned, but also the method adopted in studying its elasticity is open to serious geometrical objections. If the elasticity is required at a number of different points it will be necessary to draw a hyperbola through each point, and even then the departure of the demand curve from the hyperbola will not be easy to observe. Moreover, without some such construction, the demand curve itself is very deceptive: thus, in the present instance, the only place where the curve is

slope of this curve gives the incremental revenue required for the construction shown in Fig. 3.

Conclusions from Weir Curve

It will be noted that all the graphs so far plotted have the same base, namely the number of units changing hands. At this point, however, a change is advisable, since in studying revenue and elasticity it is more useful to know what energy price they are associated with, than what number of units. Furthermore, in the great majority of cases it is a drop in price that is contemplated rather than a rise, and the question is, what sales increase can be anticipated when the price is reduced from this to
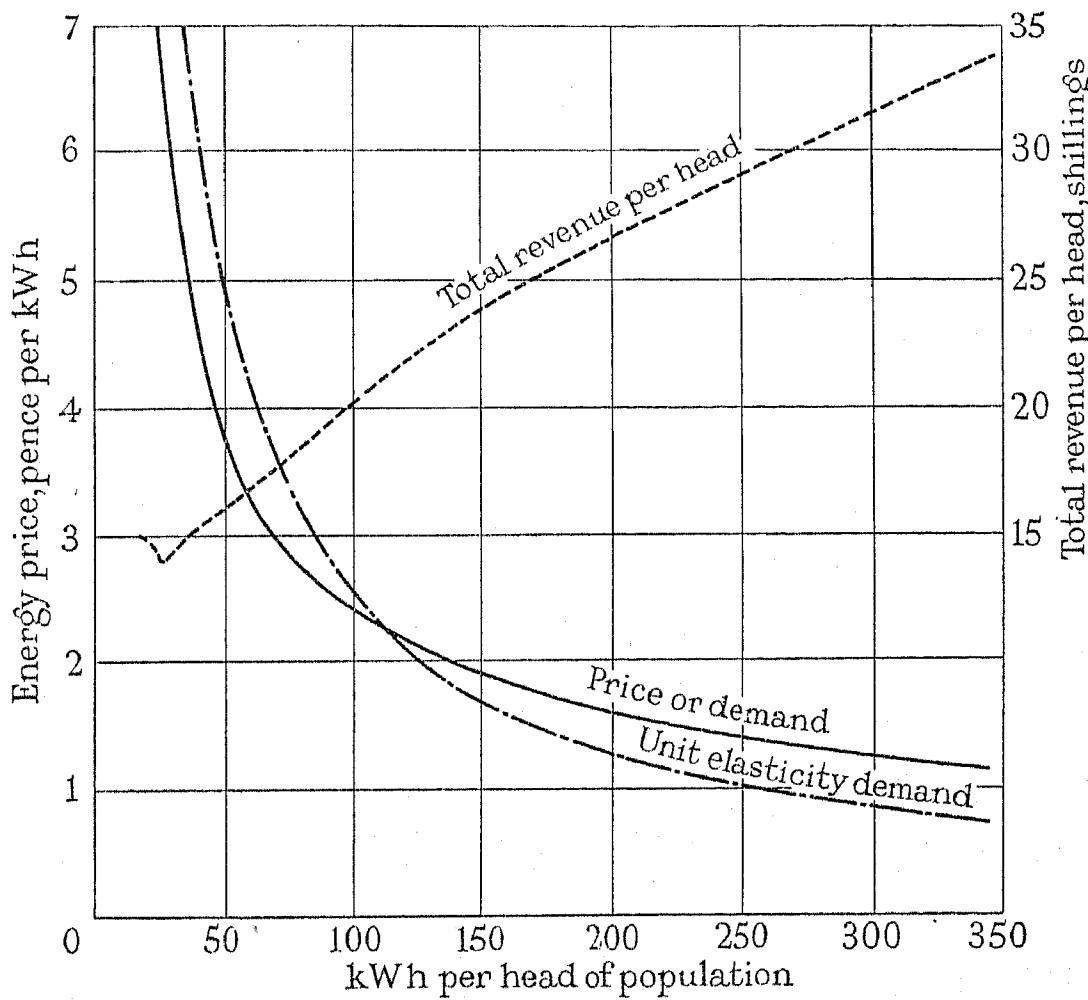
Fig. 6.—" Weir " demand curve.

less steep than a hyperbola is at the left-hand end where the steepness is superficially most apparent.

The author therefore prefers to study elasticity either from the total-revenue curve or else from the elasticity curve itself. The total-revenue curve is plotted from the demand curve by multiplying each ordinate by its abscissa and graphing the product to the same base as before. In Fig. 6 it is shown by a plain dotted line to a scale on the right-hand side. (An analogy occurs in electromagnetism, where it is found better to study the magnetic properties of steel from a curve of Φ or B against H rather than of μ against H. Actually the hypothetical D, P, and I curves in Figs. 3 and 16 were plotted from the magnetization curve for cast iron.) The total-revenue curve shows at once how the demand is behaving at different values of the load, going up and down as the elasticity varies above or below unity. Moreover, the

that? Fig. 7 therefore has a base of energy price, and this is scaled with the zero on the right. It shows the total revenue per head and the elasticity, plotted from the Weir curve mentioned above; and a chain-dotted horizontal shows the position of unit elasticity.

It would be unwise to generalize from figures which are so undifferentiated and so out of date, but there is one outstanding feature which is moreover confirmed by later results. Starting at the high-price end there is an actual fall in revenue for all price-reductions from 10d. to 7d., and the elasticity remains below $1\frac{1}{2}$ down to a price of 3d. Only when the price falls below 2d. does the elasticity rise to a value of 2 or over. In fact, the curve would seem to fall in three distinct portions. There is a portion of 7d. and over, probably representing lighting consumption by the well-to-do, who will have electricity whenever it is available and almost irrespective of the

price; there is a second portion from 7d. to 2d., representing the extension of lighting connections to the less wealthy, together with the smaller and more necessitous power consumptions; and there is a third portion below 2d., representing the general use of electric light, the larger factory loads, and the beginnings of non-lighting domestic consumption. Over the greater part of this curve, electricity is evidently serving only " necessity " ends and experiencing, in consequence, a relatively inelastic demand.

The conclusions as regards price-fixing are equally clear. Unless the elasticity is greater than unity there is no possible economic object in lowering the price, for, even

Another way of putting it is to say that when the price is high and the consumption per head is low the use is generally for " necessity " purposes and by a narrow income-group of consumers. Undertakings thus placed must be willing to plunge or they had better stay where they are: a half-hearted advance would be economically a retrogression.

Domestic Demand Curves

In presenting some modern figures as a basis for tariff construction, endeavour will be made to separate some of the variables mentioned above. Figs. 8, 9, and 10,
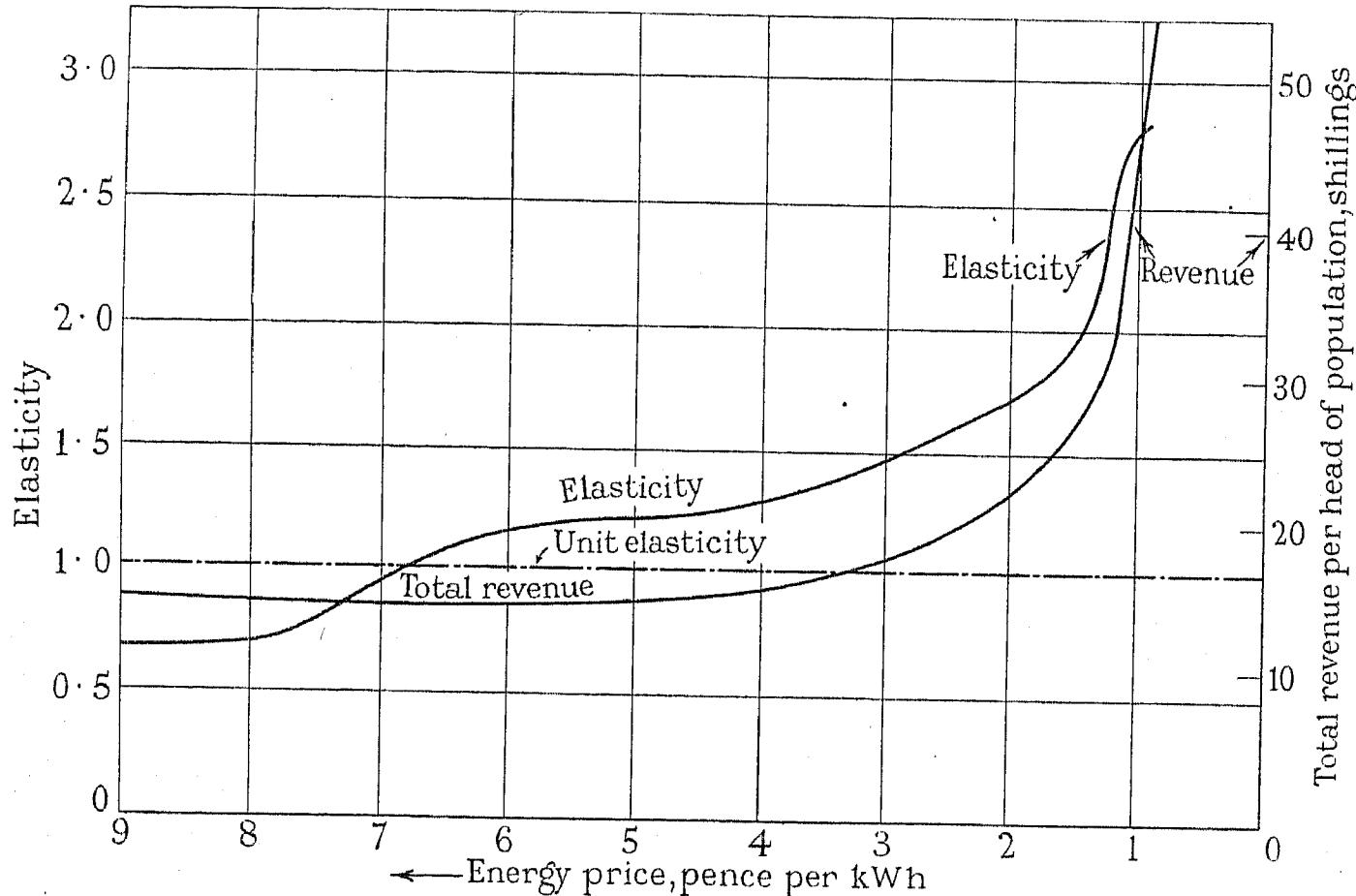
Fig. 7.—" Weir " curve revenue and elasticity.

if the additional units thus sold cost nothing at all to supply, the extra business would still not be worth having. For example, consider the case in which 100 units per head of the population served are being supplied at 1d. a unit. An elasticity of unity means that in order to increase the sales by 10 % the price must be dropped by 10 %. But selling 110 units a head at 0·9d. will bring in the same gross revenue as before,* and therefore a smaller amount of profit since the extra 10 units cannot be supplied for nothing.

In actual figures the curve indicates that, at the high-price end, a reduction of 10 % will only increase the sales by about 7 %, whereas at the low-price end the increase is 20 %–30 %. It would certainly appear that when the price is as high as it is on the upper part of this range, a small reduction is quite useless economically. Such a change is not sufficient to bring electricity into the competitive field for any purpose or clientele where it is not used already, and the demand is therefore inelastic.

present as complete a picture as is thought practicable of the domestic demand from undertakings in this country. Each mark represents a separate undertaking (crosses for local authorities and circles for companies), and every undertaking supplying 10 million units or more a year is included. Together these account for 88 % of the total domestic units sold, and may therefore be regarded as fairly representing the whole field of domestic supply. The figures relate to the year 1934–5.

Fig. 10 shows the overall demand in units per head of the population (c), while Figs. 8 and 9 show the two components of this, namely units per consumer (a) and consumers per head (b). It will be evident that the overall demand is the product of its components, or $c = a \times b$. In plotting the component curves, the number of domestic consumers was taken as 90 % of the total number of consumers in the undertaking's area as given in the Commissioners' Return. Reasons for assuming a proportion of about this magnitude are given in the recent paper by Mr. J. A. Sumner.*

* Since the changes are finite and not infinitely small, the results are only approximate.

* Journal I.E.E., 1937, vol. 81, p. 429.

Lighting and domestic units per consumer (a)
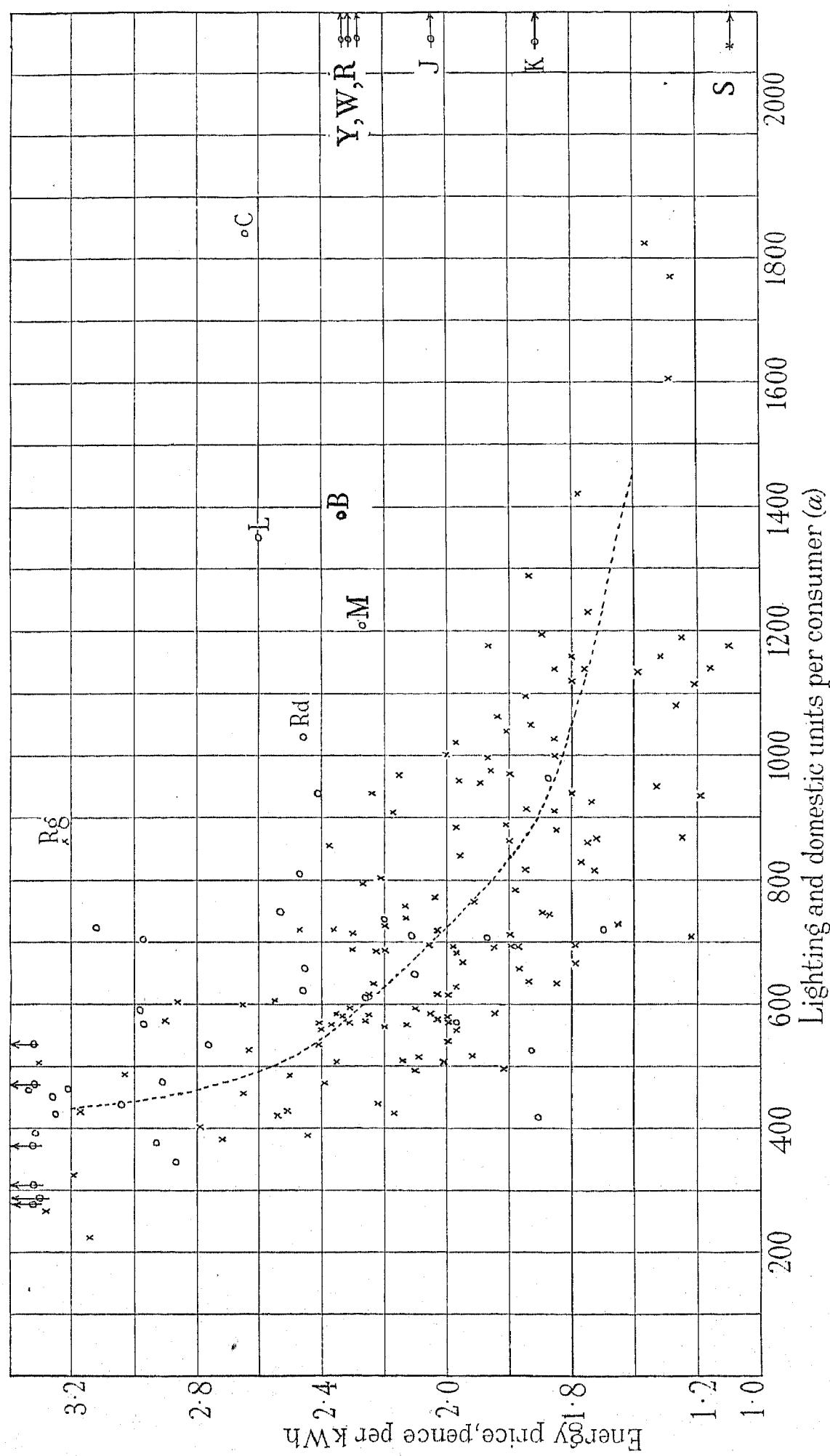
Fig. 8

Rg = Borough of Reading
Rd = Richmond (company).
M = Metropolitan.

L = London Electric Supply.
B = Brompton and Kensington.
C = Chelsea.

Y = City of London.
W = Westminster.
R = Charing Cross.

J = St. James's.
K = Kensington and Knightsbridge.
S = Borough of St. Marylebone.

Energy price, pence per kWh

In each case a middle (broken-line) curve has been drawn as nearly as possible between the various points. Considerable latitude is possible in plotting this curve, and only the general trend can be pronounced upon with any certainty. There is, however, one check since any abscissa on the (c) curve must be the product of the corresponding abscissa on the (a) and (b) curves. The lines in the Figures satisfy this condition at all points, and in fact it was of the greatest assistance in drawing them.

About a dozen of the points lie right off the curve, for reasons which will usually be obvious. These points

They show the three corresponding elasticities, namely those of units per consumer (a'), consumers per head (b'), and units per head (c'). In the case of elasticity the overall figure (units per head) is the sum of the other two,

or
$$c' = a' + b'$$

(This is proved in the Appendix.) For reasons already stated, the scale of abscissae in Fig. 11 is price per unit, with the zero on the right-hand side.

Taking the top curve, showing overall elasticity, the following points should be noted. Above 3d. per unit the
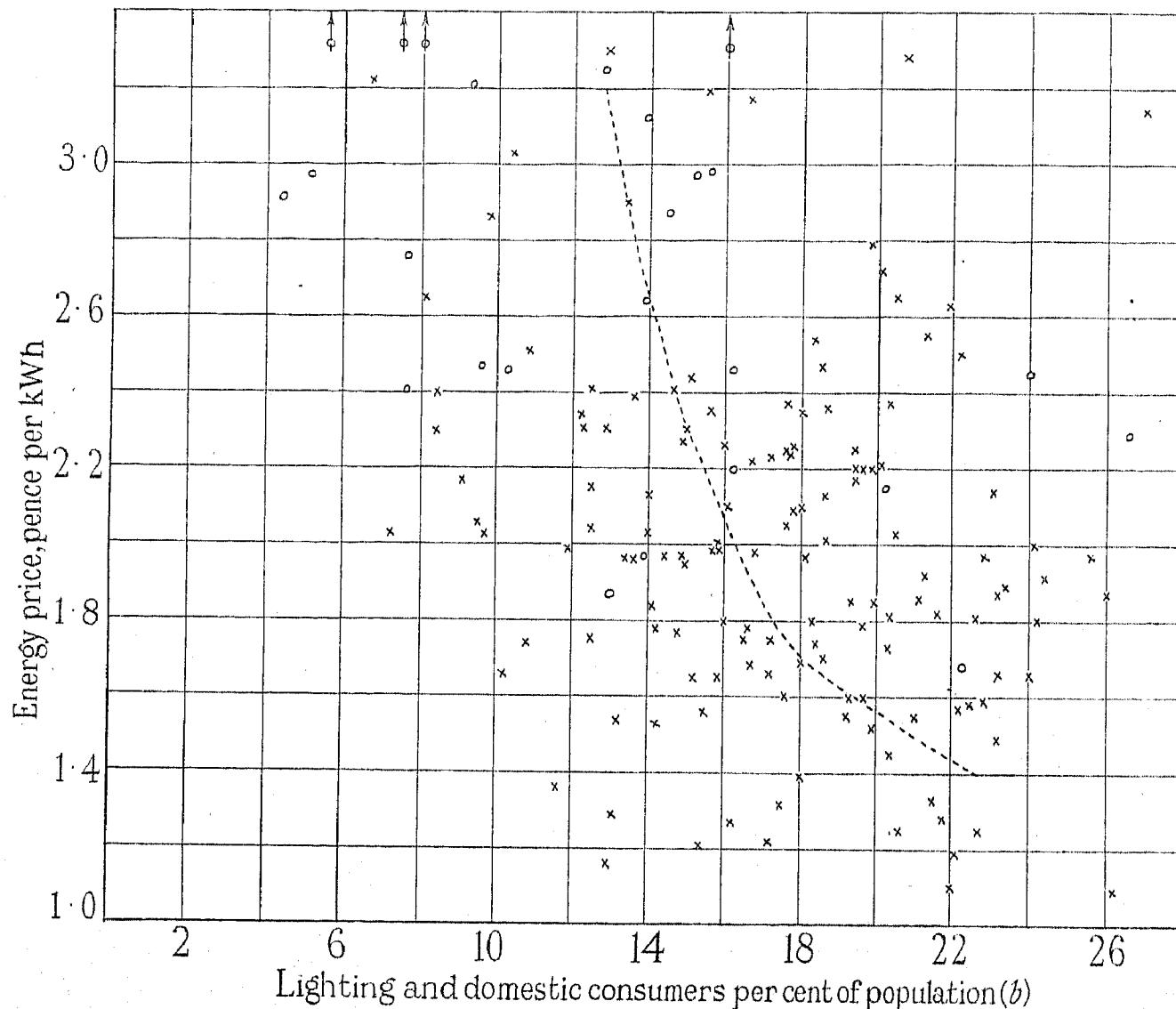
Fig. 9

represent wealthy residential or shopping areas (chiefly supplied by London companies) in which a high price has not prevented a high consumption. There is also one case (Poplar) of the contrary set of conditions. The commercial load (shop lighting, etc.) is also a disturbing factor in London. Most of these outlying points only appear on the (a) graph (units per consumer), because in many cases the population of the area of supply is not given and would be very misleading in the case of a metropolitan area. Points which lie off the scale of the graph but not off the curve direction are indicated by arrows.

Domestic Elasticity Curves

By reading off ordinates from the demand curve and taking differences the curves of Fig. 11 were plotted.

elasticity is actually less than unity. Price reductions at this point are economically unsound, even if energy costs the supply undertaking nothing at all. Even with an elasticity of $1\frac{1}{2}$, the selling price should not be less than 3 times the cost if profits are to be maintained. Hence it may be said that unless the overall price can be made less than $2\frac{1}{2}$d. it is economically preferable to raise the price rather than lower it. At 3d. or over, even the gross revenue will increase with increase of price, and of course profits will increase still more since less units will have to be supplied.

Considering next the more desirable portion of the curve, at prices below $2\frac{1}{2}$d. the elasticity rises to 2 and price reductions start to become an economic proposition. The selling price here need only be double the cost for profits to be a maximum. Between 1·8d. and 1·5d. the

Fig. 10

Lighting and domestic units per head of population (c)

Energy price, pence per kWh
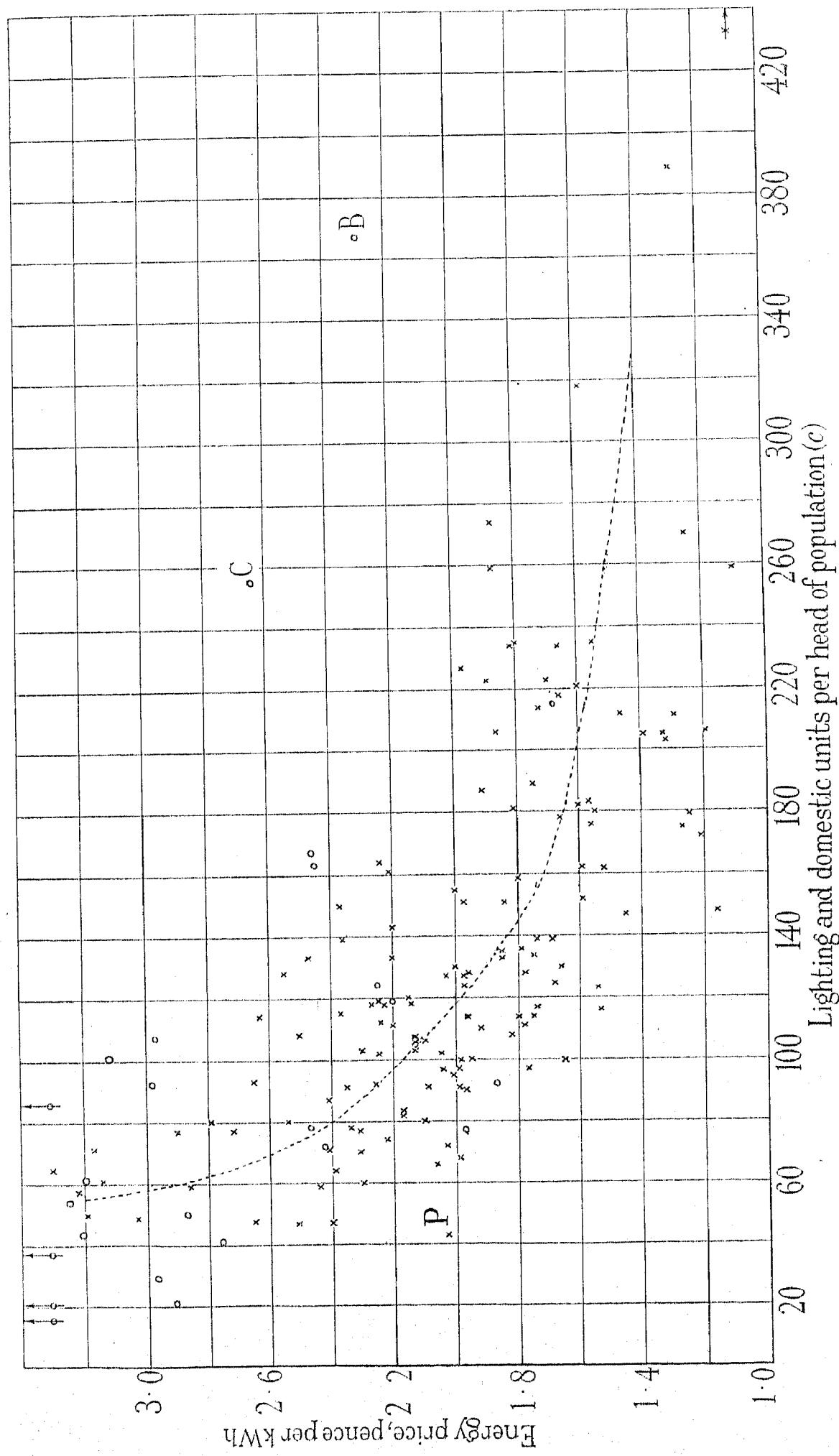
P = Poplar.

C = Chelsea.

B = Brompton and Kensington.

elasticity has a further and very marked rise, though it shows a tendency to flatten out somewhat at 1·5d. (the data are barely sufficient to establish this point). Elasticities of 3 and over are fully obtainable in the neighbourhood of 1·5d., and until the elasticity figure drops to 2 or less there is no appearance of anything like saturation. Taking the maximum elasticity figure, namely $3\frac{1}{2}$, and assuming for example a supply cost of 1·2d., the correct price on a profits basis would be given by

$$P = S\frac{E}{E-1} = 1\cdot2 \times \frac{3\frac{1}{2}}{2\frac{1}{2}} = 1\cdot6\text{d. (approximately)}$$

and this agrees with the construction shown in Fig. 12. (S is the supply cost, and the equation is proved in the Appendix.)

units, these should be taken as of the order $\frac{3}{4}$d. at the 2·5d. mark and $\frac{1}{2}$d. at the 1·5d. mark.

There are certain broad conclusions which may be drawn. Above 3d. the consumption is almost entirely in the "necessity" lighting group, elasticity is low, and small price-reductions are useless. As the price is reduced below 3d. there are two marked rises in elasticity, occurring at about $2\frac{3}{4}$d. and $1\frac{3}{4}$d. respectively. The first of these probably represents the beginnings of non-lighting consumption. The "follow on" or heating rate is here about 1d. or $\frac{3}{4}$d. and electric heating becomes a possibility. The second big rise (at $1\frac{3}{4}$d. or, say, $\frac{1}{2}$d. marginal) probably refers to the full development which accrues when electric heating becomes an attractive proposition.

The component parts of the overall elasticity are also of
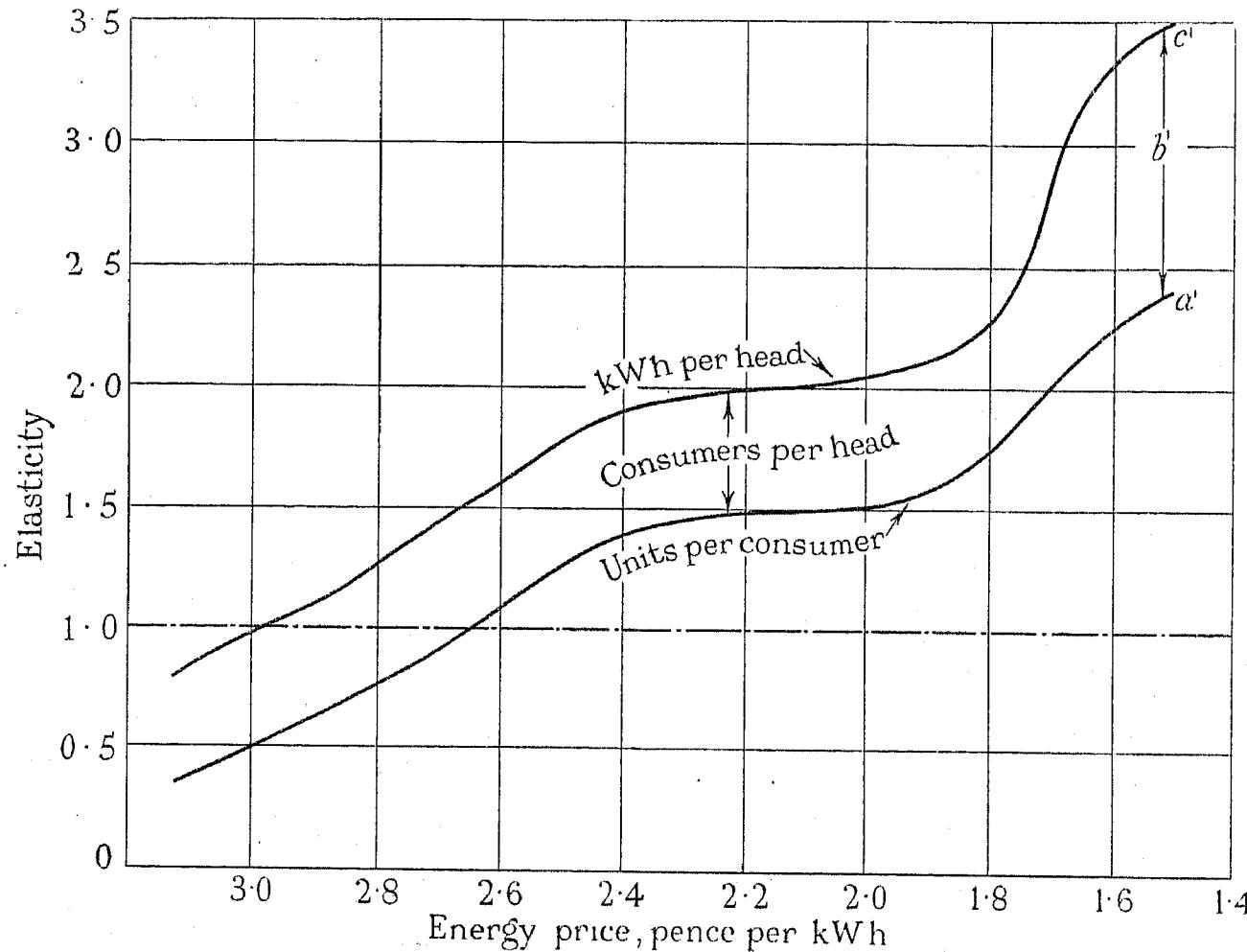
Fig. 11.—Domestic elasticities.

There is one important point regarding the price scale in Figs. 8 to 11. These show the *overall* price per unit for domestic consumption, whereas the economic determining factor is the *incremental* price. This means that the curves really apply to considerably lower energy-prices than those shown. Thus an overall price of 1·5d. will include undertakings in which the heating or follow-on rate of a two-part tariff is, say, $\frac{1}{2}$d. and in which the majority of the consumers are taking full advantage of this tariff.* The overall price of 2·5d. will represent, say, a $\frac{3}{4}$d. follow-on rate and a rather smaller proportion of fully developed consumers. Since the economic choice is determined by the marginal price of the additional

some interest. The elasticity of consumers per head of the population is small and fairly constant at a figure of about $\frac{1}{2}$. This means that a 1 % reduction in price will produce about a $\frac{1}{2}$ % increase in the number of consumers. The elasticity of units per consumer makes up much the greater part of the total elasticity and is, moreover, the element that varies with the price position. That is to say, the variations in elasticity at $2\frac{3}{4}$d., $1\frac{3}{4}$d., etc., discussed above, are almost entirely due to the consumption response of existing consumers rather than to any growth in their number.

Incremental-Revenue Curve

It is shown in the Appendix that there are two derivatives from the demand curve, namely elasticity and

* In a house with a fixed charge of £4 per annum and a running charge of $\frac{1}{2}$d. per unit the overall price would be 1·5d. per unit when the consumption was 960 units per annum.

incremental revenue, either of which may be used for purposes of tariff construction. The first method has been employed in the previous Section, and the second method will now be illustrated.

In Fig. 12 is shown a portion of the demand curve (D) reproduced from Fig. 10, and below it is shown the corresponding incremental-revenue curve (I). In order to illustrate how demand economics can be utilized in price-fixing, let it be supposed that the cost of supply is constant, namely 1·2d. per unit (line S). This line would cut the D curve to the right of the Figure at a

It will be noted that the I curve becomes negative on the left (elasticity below unity) and has a peak in the middle. (The actual I curve showed two distinct peaks, which have been merged into one in the Figure in order not to complicate the foregoing explanation.) In fact, the downward sweep of the I curve is part of the vicious circle of high prices and low consumption. To the left of this point it does not pay to reduce the price; it is more profitable to increase it, and contract the sales still further. The only way to break the circle is to make a big price-reduction on to the other side of the peak.
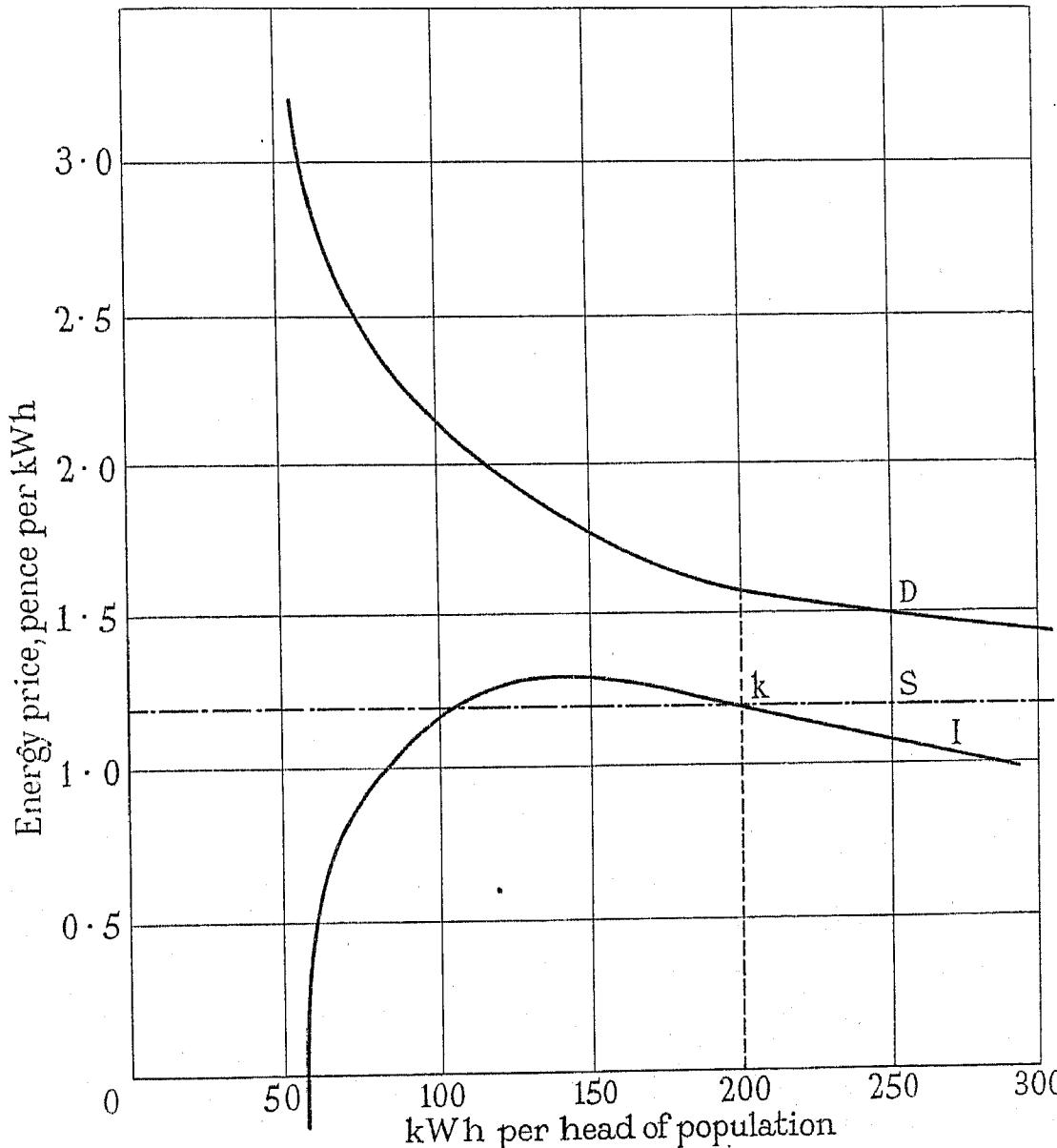
Fig. 12.—Incremental revenue.

point representing about 420 units per head. On a " costs " basis the price would be fixed at this point, since it covers all expenses and brings in the maximum possible load.

At any higher price and smaller number of units there would be a surplus or profit per unit represented by the vertical height of D above the horizontal line 1·2. If this intersection be multiplied by the number of units it will give the total profit obtained, and this total is a maximum at the point k. On a " profits " basis the price would be fixed here, namely at 1·6d., and would bring in a load of 200 units per head (this confirms the conclusion made previously). The total profit would then be 0·4d. × 200, or 80d. per head.

Single Undertaking (Domestic)

It will be perceived that the above analysis suffers from two serious flaws. It is unable to distinguish between lighting and heating consumption, and it is worked out on a basis of overall price. Unless the tariff is a flat-rate one the overall price is a composite figure and does not represent the marginal price, which is really the determining factor. Thus, while much useful information can be obtained from these curves, it is difficult to apply them quantitatively.

One way of getting over both these difficulties is to take a single undertaking giving lighting and heating on separate meters and having sufficient history to illustrate a number of price-changes: such an undertaking is
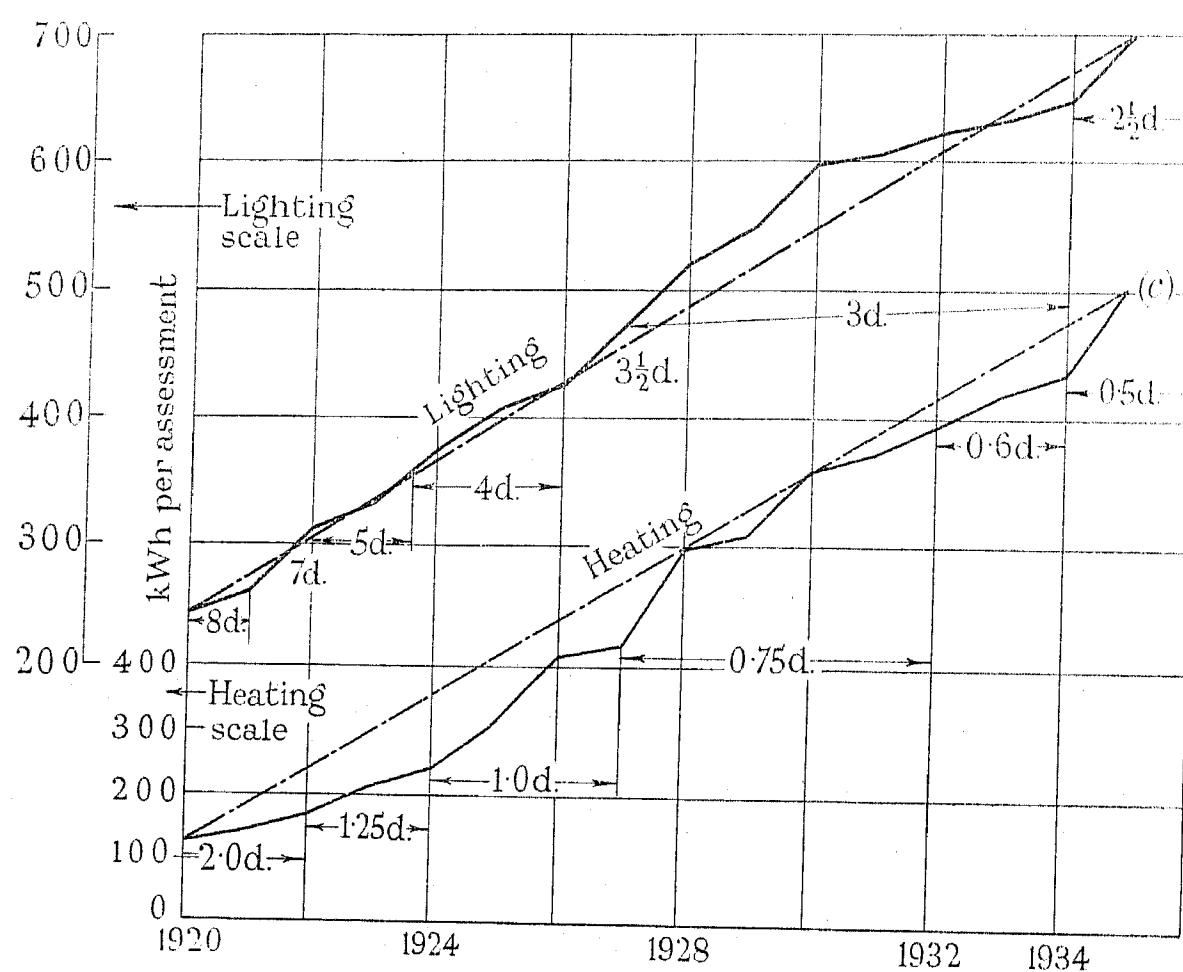
Fig. 13.—Single undertaking.
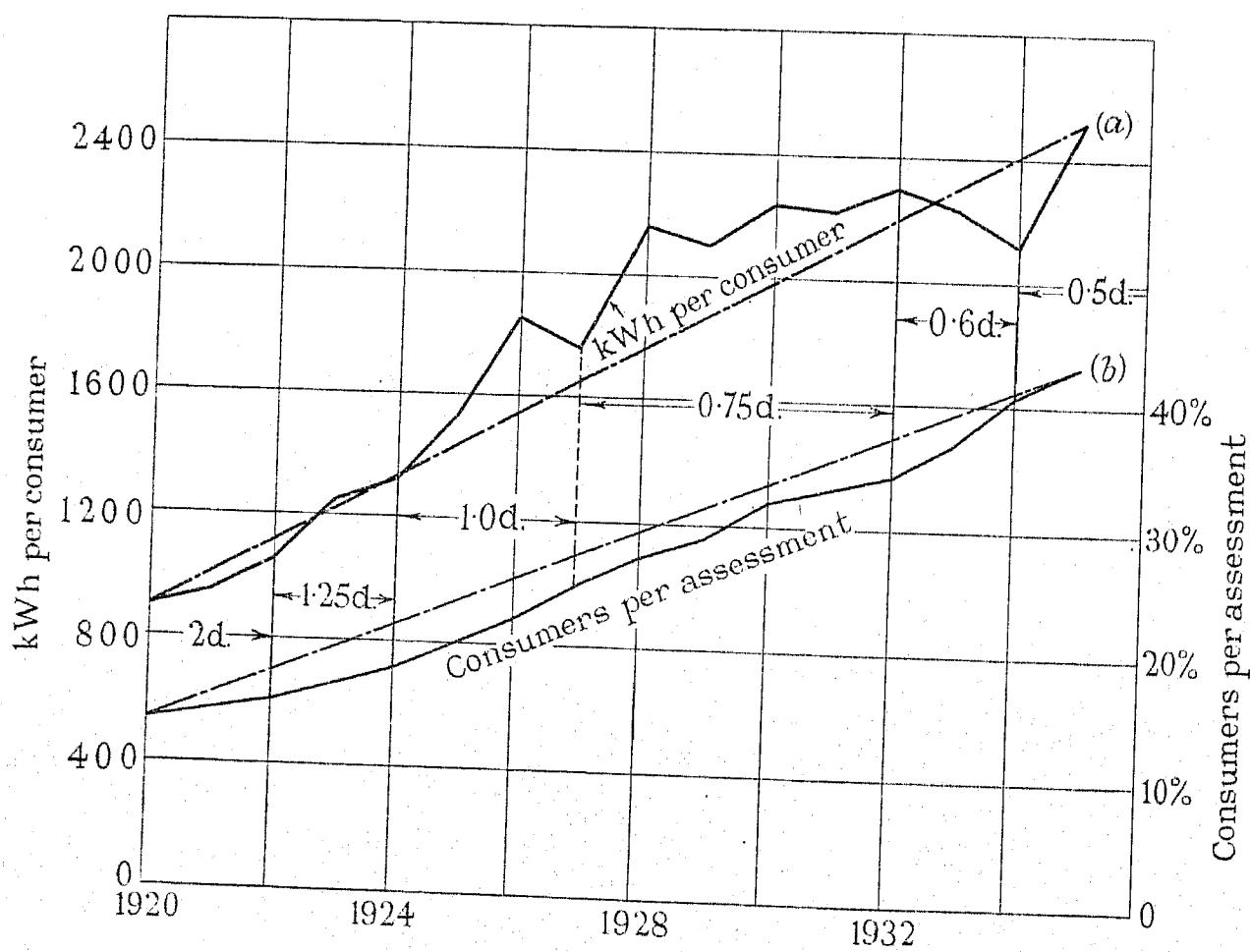
Fig. 14.—Heating-curve components ($a \times b = c$, Fig. 13).

Hampstead.* Until the end of the period illustrated below, all the domestic electricity in Hampstead was sold under the two-rate plan, and figures are available not only for the numbers and prices of the units but also for the number of separate connections of each sort. The total period covered is 15 years, from 1920 to 1935, and therefore starts after the War terminated and extends over a time during which there have been no very great changes in the general price-level. Another difficult variable in any time-period is the number of separate households, representing the possible clientele for electrical development. Hampstead was a fairly fully built-up area even at the beginning of the period and housing developments have been relatively small, but there was a steady drift here, as elsewhere, in the direction of conversion and splitting-up of large mansions and the erection of blocks of flats on the sites of others. In order to allow for this, the total number of separate assessments for local taxation was obtained for each

curve is flatter than the average indicated by the dotted line.

Both curves were analysed into their component parts, and for the heating case these components are shown in Fig. 14. Taking the upper curve of units per consumer, this shows a very distinct concavity for each of the price-changes, whereas the curve of consumers per assessment shows no such correspondence.

It is impossible to express the elasticity pure and simple, because of the change of date. In a period of 15 years there have been extensive changes in housing and domestic habits, use of wireless, etc., to say nothing of the steady pressure of publicity, the increased prestige of electricity, and the rising standard of living. A growth in consumption over the period is therefore only partially attributable to the elasticity *per se*, i.e. the response to price-changes. What the figures can bring out, however, is the difference in the relative elasticity of lighting and heating.

Table 2

	Price	Units per consumer	Consumers per assessment	Units per assessment
		Lighting		
At 1920	8d.	368	0·66	368 × 0·66 = 243
At 1934	3d.	560	1·15	560 × 1·15 = 643
Mean annual change	− 6·8 %	+ 3·1 %	+ 4·0 %	+ 7·2 %*
		Heating		
At 1920	2d.	916	0·14	127
At 1934	0·6d.	2 130	0·41	880
Mean annual change	− 8·2 %	+ 6·2 %	+ 8·1 %	+ 14·8 %*

* This figure is approximately equal to the sum of those in cols. 3 and 4.

year, and the electricity sales were divided by this figure. The overall consumption, instead of being units per head of population served, thus becomes units per assessment, while the components of this are units per consumer and consumers per assessment. The last figure slightly exceeded 100 % in the case of lighting connections in 1935, indicating that there were rather more lighting consumers than ratepayers—a condition of fairly complete saturation for lighting connections.

Fig. 13 shows the overall total (units per assessment) for the two loads, lighting and heating, plotted to a time-base, the lighting ordinate scale being twice that of the heating. A chain-dotted line joining the two ends of each curve shows the average rate of growth and helps to indicate where the growth has been different from the average. Horizontal arrowheaded lines show the price ruling at any time, and a certain downward concavity in each price section indicates the response to this price-change. This is more noticeable in the heating than in the lighting curve, though even in the latter case it will be seen that on the portions where the price remains constant (e.g. 8d., 4d., and 3d.) the general tenor of the

For this purpose the same period has been taken as before, but excluding the last year, i.e. the 14 years from 1920 to 1934. This period has the advantage of starting after the War, with its erratic price-levels and artificial reduction of lighting consumption. It also terminates where a new price commences for both heating and lighting. Instead of giving the total price-change over this period, the author has taken the 14th root of this, so as to show the average percentage change per annum, i.e. the mean ratio of each year's figures to those of the previous year. The results are displayed in Table 2.

In the case of lighting there was an average price-reduction per annum of 6·8 %. This resulted in a total sales increase per annum per household of 7·2 %, made up of a 3·1 % rise in units per consumer and a 4 % rise in consumers per household. For heating, an almost equal price-reduction ratio gave increases of just about double those of lighting in each case. If the percentage change in overall units (i.e. per household) be divided by the percentage change in price, a figure of 1·06 is obtained for lighting and 1·80 for heating. This figure might be termed the relative or annual elasticity, or elasticity-plus-time factor, since it is the combined result of pure

* The author is indebted to Mr. H. Brierley, engineer and manager of the Hampstead undertaking, for the results recorded here.

elasticity and the various time elements enumerated above.

Comparison Figures

For purposes of comparison Table 3 gives figures referring to the total domestic consumption of all authorized undertakings. The first line refers to the 14 years ending 1935, i.e. practically the same period as in the Hampstead case. As before, the 14th root of the change ratio has been taken, so as to show the mean annual percentage change. It was not until 1927 that the Commissioners started to list the number of consumers, and thus the second line of the Table refers to the last 9 years only. This line shows not only the overall consumption per head (*c*) but also its component parts (*a* and *b*).

It may be thought that the Hampstead figures show up poorly by comparison with these last, since Hampstead gave a relative elasticity of 1·06 and 1·80 for lighting and heating whereas these latter give 2·2 for domestic supplies as a whole. When the overall figure is analysed, however, it is found to be due entirely to a very high ratio of consumers per head of population, namely 15·8 % increase for 6·9 % decrease in price, giving an

be carried out over a period of years and over a series of price-changes, either for a single undertaking or else for an aggregate, the area served being the same for each point considered. In order to eliminate a further variable, namely the state of employment, the units in the following case will be divided not by the population but by the average number of insured persons in employment during the year. (This method leaves out of consideration all agricultural workers.)

The results now to be given refer to all authorized undertakings, and cover the last 14 years for which figures are obtainable. Fig. 15 shows the units per worker and the total revenue per worker for the whole period (full lines) while below is a plain dotted line showing the price. A straight chain-dotted line shows the mean slope of the units curve, and there is a distinct though small downward concavity resulting from each period of price-reduction. As in every other curve plotted in this paper, price-reductions at the high-price end give a fall rather than a rise of total revenue; and in this case it is only when the price comes below 1d. that the revenue goes consistently upwards. As in the previous cases, it is possible to regard the 14 plotted values as a series of 13 change ratios. Taking the 13th root of the total

Table 3

Length of period (ending 1935)	Mean annual change in:—				Ratio of changes (*c/p*) (relative elasticity)
	Price (*p*)	Units per consumer (*a*)	Consumers per head (*b*)	Units per head (*c*)	
14 years	— 7·5 %	—	—	16·5 %	2·2
9 years	— 6·9 %	— 0·4 %	15·8 %	15·4 %	2·2

elasticity ratio of 2·3. The units per consumer have actually dropped by some ½ % per annum compared with a rise in Hampstead of 3 % (lighting) and 6 % (heating) for about the same price-change. In fact, the elasticity throughout the country is almost entirely due to the taking-on of fresh consumers, and such an elasticity is far from being the most profitable type for the undertaking.

Industrial Demand

The method of a target diagram of separate undertakings is of little use for the industrial load, owing to the absence of a common denominator. The differences in character—urban and rural, industrial and residential—have a much greater effect upon the power load than upon the domestic one. We all live in houses, and every house is a possible electrical market; but we do not all work in factories, and the potential power load is very unevenly distributed. Thus it follows that while domestic units per head form a tolerable comparison between different areas, industrial units per head are entirely useless. Equally impossible is any splitting-up into units per consumer or consumers per head: since the number of power consumers is so small a fraction of the total, it cannot even be guessed at with any accuracy. As a result of these difficulties, power comparisons must

ratio will give the average ratio which each year bears to the previous year. This gives the following results:—

Mean annual change in price (*p*)   = — 6·7%
Mean annual change in units per worker (*c*) =   9·5%
Relative annual elasticity (*c/p*)   =   1·42

The last figure may be compared with the Hampstead figures of 1·06 for lighting and 1·80 for heating. The industrial relative elasticity appears to lie about midway between these other two.

Final Conclusions

It was said at the commencement that the main purpose of the paper is to explain the operations of supply and demand rather than to elucidate the actual shapes of the curves. But, working both on *a priori* grounds and also inductively from such data as there are, it may be surmised that the lighting load has an elasticity of about 1, the industrial load about 1½, and the non-lighting domestic load from 1½ to 3 or more, depending on the price position. It would certainly appear that the elasticity for purely lighting supplies is seldom much over unity. It follows that reductions in the lighting rate (or, what amounts to the same thing, in the fixed portion of an "all in" tariff) are never justified commercially.

They are a method of distributing surpluses, not a method of acquiring them.

Even if there are surpluses to distribute, the difference in the two elasticities means that the money will go much farther if spent on heating than if spent on lighting reductions, and will therefore give greater benefit to the consumers. To put it in another way, let it be supposed that a surplus of 10 % appears in one year and that it is proposed to distribute this by a price-reduction the following year. If the surplus is allocated to the lighting consumers it will only be possible to grant, say, a 5 % reduction in the tariff without incurring a deficit, and this will give only a 5 % increase in sales; whereas if

Lest the above paragraph should lead one into a feeling of optimism, it is well to remember that the process of price-fixing, here set out with all the appearance of mathematical precision, in practice can rarely become an exact science. Precise data, especially for the demand, are unobtainable: the curves, though excellent for illustration, usually fail when it comes to calculation, and serve rather to show the process than to indicate the results. Even when the facts are undisputed, policies may differ; and in a changing scene of costs and values the careful plotting of curves is like making an accurate plan of the room before embarking on a game of blind man's buff.
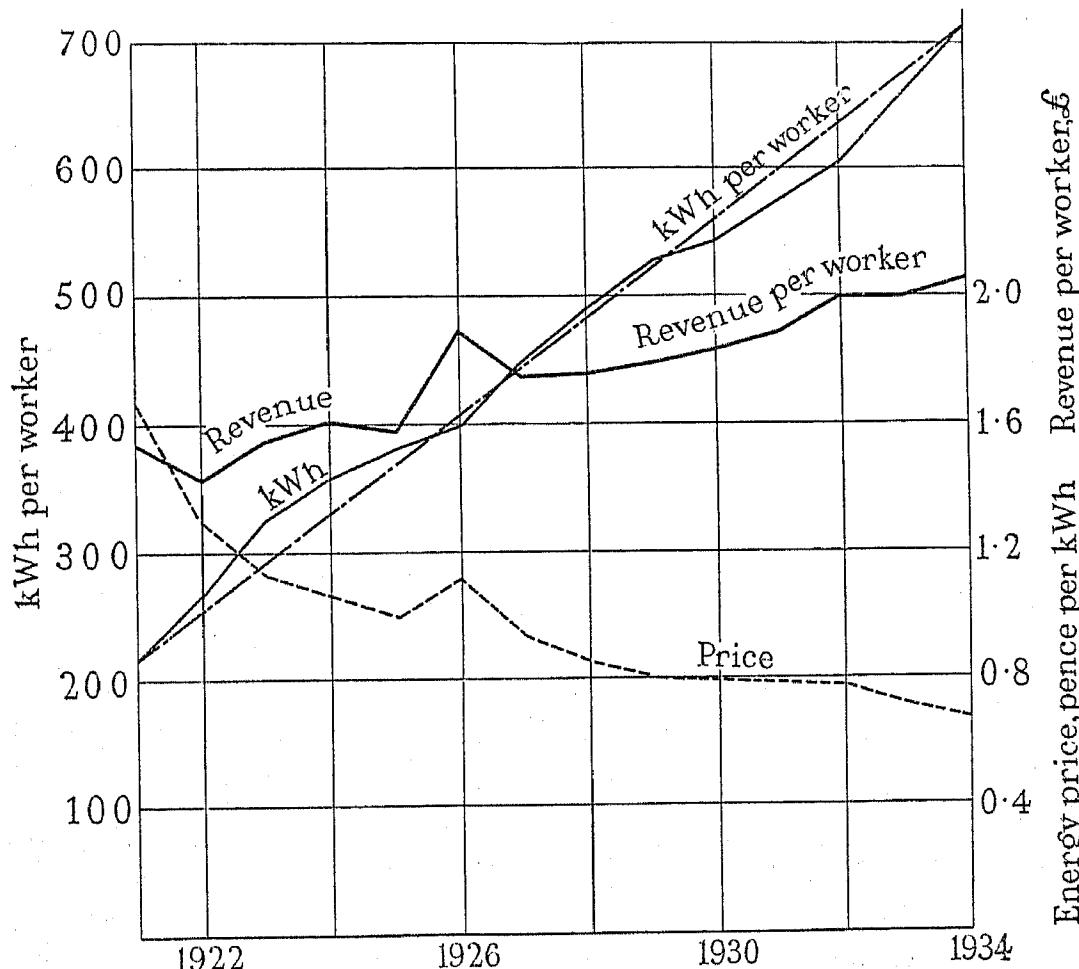
Fig. 15.—Industrial results.

the surplus is allocated to the heating consumers it will be possible to grant a 20 % or 30 % decrease in charge without deficit, and to realize thereby something like a 100 % increase in sales.

The outstanding feature of the general survey of domestic demand was the very high elasticity at the lower end of the price range—values of 3 or over for mean prices of about $1\frac{1}{4}$d. (or follow-on prices of, say, $\frac{1}{2}$d.). Considering that this figure shows the average effect of both lighting and heating and that the former only contributes a much smaller figure, the elasticity of the latter must be higher still. Under these circumstances a reduction in the heating rate or in the follow-on rate of a two-part tariff will frequently be possible without any ultimate loss in revenue whatsoever. Moreover, if the incremental cost is also known with some accuracy, it actually becomes possible to plot the " correct " tariff, and perhaps to visualize the beginnings of a science of tariff construction.

Time and Other Factors

One matter of extreme importance omitted from the present paper is that of time and publicity. Demand has here been isolated and treated as though it functioned automatically *in vacuo*, and as though a drop in price would produce a given increase in sales, without the operation of human labour or human ingenuity. Actually, sales elasticity is very far from being automatic and immediate, as can be well seen from the example quoted in Table 4.*

It will be seen that after 9 months' operation of the new tariff the proportional increase in units was appreciably less than the drop in price. The relative or annual elasticity figure was therefore less than unity, so that a smaller revenue was obtained in March, 1937, than in March, 1936. Since the extra units must have cost

* Extracted from a letter in the *Electrical Review* (1937, vol. 120, p. 696). A comparable example taken over a longer period was given by Prof. Miles Walker (*Journal I.E.E.*, 1936, vol. 79, p. 511).

something, the immediate results would show an appreciable drop in profits, although, of course, the ultimate results might be quite different. A factor which is related to publicity is that of the facilities for obtaining a supply. Questions of street cabling, assisted wiring, and the support or opposition by landlords of old premises, will obviously affect the elasticity of consumers per head, though not the elasticity of units per consumer.

Another considerable omission from the paper is what is called " human nature," or more correctly the non-

Such a curve could be scaled in pence and evaluated by comparison with other utilities. It would start from the origin and would run upwards, somewhat in the manner of a B–H curve. The mean utility (U/N) would decline slowly, since the mean satisfaction per unit would go down with the number of units taken. But the marginal utility would go down more rapidly, because the added satisfaction obtained from the last unit purchased would be less than the average for the whole. Since the consumer will not purchase the extra unit unless it is worth

Table 4

Date of quarter	March, 1936	March, 1937	Change ratio
Price of unit of electricity ..	1·0d.	0·48d.	— 52 %
Units per consumer (a)	332	437	+ 32 %
Consumers (b)	2 878	3 082	+ 7 %
Units (millions) (c) = (a) × (b) ..	0·957	1·348	+ 41 %

rational and non-economic facets of that nature. In practice a rate must not only be fair, but must *appear* fair, and it sometimes happens that a lighting price is settled neither by supply cost nor by demand values but by sheer popular sentiment. But the biggest gap in the work is still the need for facts. The theory of supply and demand makes an imposing façade to the tariff construction, but until more data are available it is little better than a coat of scientific paint on a building that is pure empiricism.

APPENDIX
Note on Terms

The word " unit " is employed as a conveniently vague term to indicate the single commodity or unit of output or service. When the same principles are applied to electricity supply the word will stand for a kilowatt-hour. The symbol N is employed to indicate the number of these units changing hands, and is the single base of most of the curves in the paper. When a number of curves are plotted with values of N as abscissae (as in Fig. 16) they are labelled with initials for the quantities plotted as ordinates.

The words " marginal " and " incremental " are used indiscriminately for the same thing, namely dY/dN, where Y is some variable dependent on N. The former word is more familiar to economists but the latter conveys more to the engineer, and in order to link the two sciences it was found best to make use of both words.

Price, Revenue, and Profits

The best starting-point in a consideration of curve relationships is the demand or price curve, indicated by D in Figs. 1 to 3 and by P in Fig. 16. This curve shows the price per unit P at which any number of units N will be bought. It may primarily refer to a single consumer, and then, with a change of base scale, to all consumers in a given area.

[In theory it might be possible to derive the demand-price curve from a curve plotting the total utility or satisfaction (U) obtained from the use of the electricity.

his while, this marginal utility would be the (flat rate) price of *all* the units. Hence the price curve would be the slope of the total-utility curve, or $P = dU/dN$. Such a derivation is only of academic interest, however, and the best starting-point is the price curve itself.]

The first step is to multiply each ordinate of the price curve by its abscissa, to give the total-revenue curve ($R = PN$). The slope of this, giving the marginal or
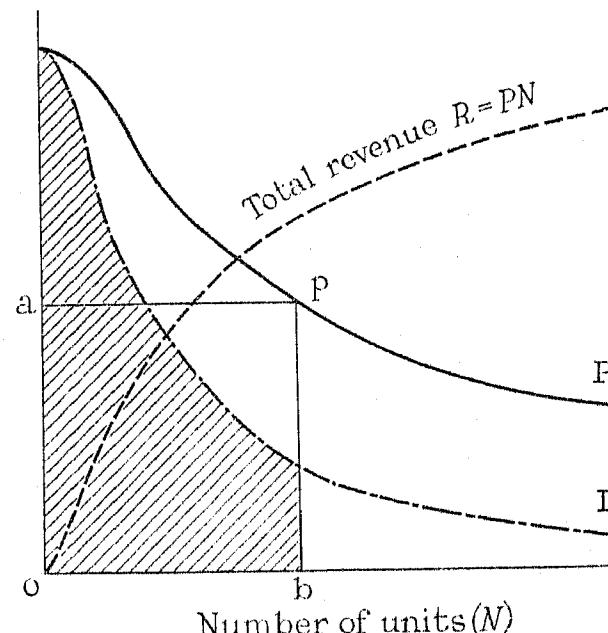
Fig. 16.—Derivation of curves.

incremental curve, is then plotted. This curve is represented by

$$\frac{dR}{dN} = \frac{d}{dN}(PN) = P + N\frac{dP}{dN}$$

Now the slope of the price curve is always negative, so that the incremental-revenue curve lies below the price-curve by an amount equal to N times the slope of the price curve. From Fig. 16 it will be seen that the curve I starts with the curve P on the y-axis, and would join it again if P became horizontal; but elsewhere lies below it. [If P does not cut the y-axis, I will lie below it

entirely. Thus if P is hyperbolic ($PN =$ a constant) R will be a horizontal straight line and I will be zero. If P is less steep than a hyperbola, on account of an elasticity less than unity, I will be negative.]

At any point p the area under the I curve (shown shaded) equals the rectangle $oapb$. For the rectangle represents an actual occurrence, namely the number of units sold multiplied by the mean price per unit (= total revenue). The shaded area under the I curve represents a hypothetical occurrence to give the same result, namely the sum of each separate unit (from zero) multiplied by the amount by which it would have swelled the total revenue. Mathematically, the height of the incremental-revenue curve equals dR/dN, so that its area when plotted to a base of N equals R. In a similar way, the supply-cost curve S shows the rate of change of cost with numbers, so that its area gives the total cost. It follows that profits are greatest when the area between the I and S curves is a maximum, i.e. where the two curves cross (k in Figs. 3 and 12).

Elasticity and Profits

The purpose of this Section is to show the relationship between elasticity and incremental revenue.

The elasticity, E, has been defined as the rate of increase in units divided by the rate of decrease in price, or

$$E = \mathbf{L} - \frac{\delta N}{N} \div \frac{\delta P}{P} = -\frac{P}{N} \cdot \frac{dN}{dP}$$

But $\qquad I = P + N\frac{dP}{dN}$ (see above)

$$= P\left(1 + \frac{N}{P} \cdot \frac{dP}{dN}\right)$$

$$= P\left(1 - \frac{1}{E}\right)$$

If the elasticity is unity the incremental revenue is zero, and if the elasticity is less than unity I is negative. This agrees with the definition of unit elasticity as meaning constant revenue whatever the number sold. If the elasticity is 2, the incremental revenue is half the price per unit, so that if the price were 1d. a drop in price sufficient to bring in one extra unit would bring in $\frac{1}{2}$d. extra revenue. This can easily be seen by taking actual figures, as follows: An elasticity of 2 means that a price-reduction of 1 % produces a sales increase of 2 %. Instead of, say, 100 units being sold at a price of 1d., the sales become 102 units at a price of 0·99d. (total revenue 101d.), i.e. the extra 2 units will increase the revenue by 1d., or $\frac{1}{2}$d. each.

If the elasticity is 3, then every extra unit sold through price-reduction will increase the revenue by only $(1 - \frac{1}{3}) = \frac{2}{3}$ of the price per unit (since the reduction affects all the units sold). In such a case, if a reduction is proposed from an existing price of P, the extra units will only swell the revenue by $\frac{2}{3}P$ each. Unless the supply cost of the extra units is less than this figure, such a reduction is not commercially justifiable. (It may, of course, be economically justifiable, i.e. it will reduce profits but it will not produce a loss, provided the supply cost is less than P itself.)

Summing up this and the previous Section, it may be said that there are two ways of demonstrating the correct price, one employing the demand curve and the other the elasticity curve. The former may be preferable in planning a scheme *de novo*, but the latter is a better way of showing the fluctuations of load response and the desirability of changing an existing tariff. The two methods, of course, yield the same result since both are mathematically derived from the same premises.

When using the demand curve the method is to plot the three curves to the same base of N, namely the demand or price curve P, the incremental-revenue curve I, and the cost curve S. The points where S cuts P and I will represent the correct prices under "costs" and "profits" criteria respectively. When using the elasticity curve the method is to work out the elasticity E, and the incremental cost S, for the ruling price P. Price-reduction without loss of profits may then be carried out down to the point where

$$P = S\frac{E}{E - 1}$$

In symbols the results may be summarized as follows: On a costs basis (or "public authority" criterion), $P = S$. On a profits basis (or "company" criterion), $I = S$, and $P = SE/(E - 1)$.

Elasticity Components

The following symbols are employed:—

$N =$ number of units;
$H =$ number of heads of population;
$Z =$ number of consumers;
$a =$ number of units per consumer $= N/Z$;
$a' =$ elasticity corresponding to a;
$b =$ number of consumers per head of population $= Z/H$;
$b' =$ elasticity corresponding to b;
$c =$ number of units per head of population $= N/H$;
$c' =$ elasticity corresponding to c.

Then the overall consumption is given by

$$c = ab$$

and the overall elasticity by

$$c' = a' + b'$$

In words, the overall consumption in units per head of population is the product of the units per consumer and the consumers per head. The overall elasticity, or proportional change in units per head (for a given proportional change in the price P), is the sum of the separate elasticities of units per consumer and consumers per head. The former statement is self-evident, and the latter is proved as follows:—

$$a' = \frac{\delta a}{a} \times \frac{P}{\delta P}, \quad b' = \frac{\delta b}{b} \times \frac{P}{\delta P}$$

$$c' = \frac{\delta c}{c} \times \frac{P}{\delta P} = \frac{P}{\delta P}\left[\frac{H}{N}\delta\left(\frac{N}{H}\right)\right]$$

$$= \frac{P}{\delta P}\left[\frac{H}{N} \cdot \frac{H\delta N - N\delta H}{H^2}\right] = \frac{P}{\delta P}\left[\frac{\delta N}{N} - \frac{\delta H}{H}\right]$$

Hence $\quad a' + b' = \dfrac{P}{\delta P}\left[\dfrac{\delta a}{a} + \dfrac{\delta b}{b}\right]$

$$= \dfrac{P}{\delta P}\left[\dfrac{Z}{N} \cdot \dfrac{Z\delta N - N\delta Z}{Z^2} + \dfrac{H}{Z} \cdot \dfrac{H\delta Z - Z\delta H}{H^2}\right]$$

$$= \dfrac{P}{\delta P}\left[\dfrac{\delta N}{N} - \dfrac{\delta Z}{Z} + \dfrac{\delta Z}{Z} - \dfrac{\delta H}{H}\right]$$

$$= \dfrac{P}{\delta P}\left[\dfrac{\delta N}{N} - \dfrac{\delta H}{H}\right] = c', \text{ as above.}$$

(N.B.—The small changes δN, etc., have been treated as infinitely small, and calculus methods used thereon.)

BIBLIOGRAPHY

A fuller explanation of the mechanism of supply and demand (pages 185 to 188) may be found in the following books:—

Elementary. H. D. HENDERSON: "Supply and Demand."

More Advanced. JOAN ROBINSON: "The Theory of Imperfect Competition."

E. CHAMBERLIN: "The Theory of Monopolistic Competition."

For the extension of this theory to the concept of elasticity, and its application to electricity supply, there are no authorities that can usefully be referred to.

DISCUSSION ON

"LIGHTNING"*

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 16TH FEBRUARY, 1937

Mr. M. Cline: I should like to mention an incident which may throw some light on the question of protection against a direct stroke.

I was once present in a house in Central London when it was struck by lightning. An aerial placed 25 ft. above a 4-story building led the discharge into a room on the ground floor; the discharge then passed to earth at several points from the lead-in, which was suspended around the room on insulators. This wire was afterwards found to have disappeared completely for about 2 ft. at each of these places, and the wall was charred immediately opposite. The earthed aerial (of 7/22 S.W.G.) had passed the flash to earth but had disintegrated in doing so.

Inquiries made the following day elicited the fact that no neighbouring house had experienced any damage, and it is therefore assumed that even when a direct stroke occurs a metallic path of comparatively small dimensions will save a structure from destruction.

Mr. T. A. George: A photograph recently published in the *General Electric Review*, which is believed to be the only one of its kind, seems to give conclusive proof that streamers reach up from the point about to be struck and connect with the downcoming stroke. The stroke shown in this photograph struck to earth about 100 ft. in front of the camera, and the streamers are clearly shown reaching upwards. One streamer is about 6 ft. tall and another about 4 ft., while in the main stroke there is a sharp kink about 8 ft. high, with a small spur, which indicates that the stroke connected up with a third streamer.

As regards the polarity of lightning clouds; I think that the clouds change polarity during storms, because photographs have shown both positive and negative strokes from the front of a stormcloud within about 30 sec. of each other. In the open country the polarity of strokes seems to be about equally divided, yet the records of strokes to power lines taken in the U.S.A. indicate that about 95% of the strokes are negative; similar records for Europe indicate a slightly lower percentage of negative strokes. Can the author advance any theory to account for the preponderance of negative strokes? Does he think that the earth resistance will have a marked effect upon whether a storm has multiple or single strokes? Is it not possible that high earth resistance and a very large thundercloud will tend towards multiple strokes?

No mention is made in the paper of how a thundercloud maintains its charge during the progress of the storm. I think that the cold wind which is so often felt before a storm reaches a given spot is really the lower edge of a wedge of cold air which extends down from the cloud to the ground and acts like a scoop to force warm moist air up into the thundercloud.

In regard to damage from a nearby but not direct stroke; although the actual core of the lightning stroke is quite small, yet this in turn is surrounded by a region of highly active ionized air a fair number of yards in radius, and it seems possible that this extremely active air would cause damage.

I have heard of cases where lightning strokes have been recorded although the potential gradient of the air was less than 5 kV per metre; can the author offer any explanation of this effect?

I should like to mention a few reports of voltage-rises due to strokes direct to lines. A 220-kV line received a negative stroke within one span of the oscillograph station: the voltage rose to 720 kV in 3·5 microseconds, and the instruments went off the scale at 2 760 kV in 4·8 microseconds. In another case, that of a wood-pole 110-kV line, a negative flash struck about 4 miles from the oscillograph station and the voltage rose to 5 000 kV in less than 2 microseconds; which gives an estimated voltage-rise at the point of striking of 20 000 kV per microsecond.

In conclusion, there is one suggestion I should like to put forward for lessening the trouble and inconvenience caused by thunderstorms, in view of the more general extension of the principle of bulk supplies over long distances, the interconnection of various areas of supply, and the growth of rural lines. I suggest that throughout the country a record should be kept of the path and frequency of thunderstorms, the damage done to power plant, and the districts most affected. If this were done, when storms were developing in any districts information would be to hand as to the likely path of the storm, and preparations could be made in advance to meet the trouble likely to arise, by isolation or duplication of the supply to the area concerned. Such a scheme should be capable of supplying information to assist in the planning of routes for interconnectors and duplicate lines, and the selection of points of isolation.

Mr. J. M. Gibson: Some of the theories expounded by the author are new to us, and he has given us a good deal of additional information as regards others of which we previously had some small knowledge; it is to some of the latter that I should like to refer.

There are two types of *conditions* which, in this area at least, appear to influence the tendency for lightning to strike. They are:—

(i) *Geographical and topographical conditions.*—From observations made at different points it appears that in

some areas there are comparatively defined paths along which a good proportion of storms travel. The majority of the storms in this locality appear to travel from the south-south-west, passing between Harrogate and Boroughbridge along a route almost over Thirsk and Northallerton and striking the north-west corner of the Cleveland Hills—a few turning east over them, but the majority skirting them and turning slightly eastward to about Swainby or Hutton Rudby. Here the storms often divide, part going due east, but the majority going north-east towards Middlesbrough, turning eastwards there to the sea, and again sometimes dividing and travelling both ways along the coast. They thus traverse the Vale of Mowbray diagonally, and the sea end of the Tees valley.

(ii) *Geological conditions.*—It is suggested that there may be added tendency to strike where the soil is of relatively high conductivity. It is conceivable that this is so, and it is an interesting fact that in the districts in which most trouble has been experienced on rural lines in this area the soil is either of a gravelly nature or of boulder clay. Either of these may contain materials of good conductivity, and certainly both will *often* have a high water content. It is also suggested that the existence of geological faults and outcrops may influence the tendency to strike. This suggestion is very interesting, and I should like to raise certain aspects of it and give one or two examples, and also to make one or two suggestions as to additional probabilities.

As regards the question of geological faults, an outstanding example of the probable influence of these exists in this area. Here overhead lines run parallel to such a fault—almost, if not quite, over it. Damage has fairly often occurred at one particular point along its route, and in an unhappily large proportion of the cases the lines or the apparatus connected to them have been very badly damaged. The fault in the vicinity of this trouble has a 700-ft. slip without evidence of basaltic intrusion. At another point a few miles away on the line which this fault traverses it is known that volcanic material is not far from the surface, and at two points it is suspected with good reason that lightning strokes have a tendency to reach far lower depths than the ground surface. Again, at another point in the opposite direction, but still on the line of the fault, a substation quite near to the fault was once almost wrecked during a storm. On the other hand, we have no evidence that there is any particular tendency to strike along the line of the Cleveland Dyke, which in places is exposed.

The former case, however, does provide food for thought, and these are some of the questions which present themselves:—

(1) To what depth has the potential gradient in the earth's crust been ascertained, and what is its general average value compared with the figure given in the paper of 100 volts per cm. for air?

(2) Is the potential of different rock strata liable to vary and so cause liability to strike where slip has occurred at faults, or where certain strata outcrop?

(3) Does the existence of volcanic dykes (igneous rock) near to the surface and penetrating to considerable depths, and also the outcropping of whin sills, influence the tendency to strike?

(4) To what extent does underground water, either moving or trapped in rock cavities, tend to do so?

It is obvious that little of the damage that has been sustained in this area has been due to direct strokes. In this connection it is interesting to examine the following information relating to the distribution of storms over the areas across which most of our 11-kV rural lines are erected, and over which observations have been made for 3 or 4 years. The areas in question cover 712 square miles. The length of 11-kV lines erected is 334 miles, and, assuming that the conductors occupy a width of 6 ft., then the area covered by the lines is 0·38 square mile, a ratio of 1 : 1870. The number of storms observed during 1934, 1935, and 1936, was 42. The number of trip-outs of high-voltage lines was 88. Assuming even distribution of storms over the area, if each one of these trip-outs was due to a direct stroke, it would mean that 164 560 lightning flashes had reached points of discharge in those storms, or 231 strokes per square mile in 3 years.

The following are a few interesting examples of damage done by lightning to lines situated adjacent to objects which were struck. (*a*) A factory chimney was struck; and low-voltage lines adjacent, but in no way connected, were damaged. (*b*) A 66-kV line and a 20-kV line crossing each other almost at right angles *tripped out simultaneously*. The 20-kV line was damaged adjacent to the crossing, but the 66-kV line was not, although flashover had occurred at a pole nearest to the crossing point. (*c*) A church tower was struck, and a man working on a dead low-voltage line nearby received a severe shock. (*d*) In four cases recently trees within 50 yards of 11-kV lines have been struck, two of them being entirely destroyed, and at the same time insulators flashed-over on the poles adjacent to the trees.

Regarding the effects of lightning upon lines.—It is to be regretted that the author has based his examples and calculations on lines of extremely high voltage and with steel towers, such as the grid lines, which, as he himself states, are almost immune from lightning troubles. The difficulty we have to contend with is that our lines are erected on wood poles, have no continuous earth-wire, and the insulators have flashover values far below those of the author's safety line. The result is that it is difficult to compare these lines with the author's examples and calculations.

Stress is laid in the paper on the advisability of installing a continuous earth-wire above the phase conductors. With the exception of rural lines, most lines in this area have a continuous earth-wire below the conductors, usually supporting an auxiliary cable. The damage sustained on these lines has not been excessive, except on occasions when direct strokes have been suspected. The following instance of the influence of the positioning of the earth wire is particularly interesting. An 11-kV line was erected in 1907 with an earth wire slightly above the top phase-conductor. The line was a constant source of trouble during storms until about 1920, when the earth wire was replaced by one of larger section erected below the conductors and

connected to earth at more regular intervals. Since then this line has been almost immune from lightning trouble.

As regards the various types of discharge or strikes, it is improbable that we should be let off with an odd flashed or punctured insulator if a direct stroke occurred, and it may be that discharges of the ball-lightning or St. Elmo's types may be the cause of some damage. In support of this suggestion I give three examples.

The first is an extract from a report of a fault:—
"We have since received a report from a man fishing in the River Swale that due to extra heavy rain he had packed up his gear and was making his way to the road, and when almost under the line and adjacent to Pole 36 he perceived the lightning careering along the line from Leeming Bar and, arriving at the said pole, 'went off into showers of sparks.' The force of the explosion was so terrific that a blast of hot air was set up which knocked him flat on his back."

The second example refers to an 11-kV line with 0·2-sq. in. copper conductors which tripped on overload protection although also protected by an earth-leakage trip. At a point between 12 in. and 6 ft. from the insulators on a straight-line pole all three conductors were badly burnt but the insulators were undamaged.

In the third example, fire was seen travelling along the conductors in the terminating span of an 11-kV line and returning to the next pole, where the insulators were shattered (discs in tension).

FURTHER COMMUNICATION TO THE DISCUSSION BEFORE THE INSTITUTION*

Mr. G. E. Wyatt (*communicated*): Although the author suggests several means by which the charges of electricity can be separated in a thundercloud, he says very little of the means by which the very high potentials he assumes to be present are built up.

It has been shown by experiment that large currents flow from the earth to a thundercloud by point discharge from vegetation; it seems reasonable to suppose, therefore, that lightning only takes place when the rate of generation exceeds the rate of dissipation by point discharge, and the concentration of charge probably takes place more or less suddenly.

I venture to suggest that the following may give a clue to a contributory, if not the major, cause of this concentration of charge. It is known that the earth is negatively charged and that there is a difference of potential between the earth's surface and a layer of the upper atmosphere of the order of 3×10^5 volts in fine weather; therefore any body rising from the earth's surface to this upper layer of the atmosphere will carry a negative charge at a potential of approximately 3×10^5 volts to the surrounding air, assuming of course that it has lost no charge by dissipation. This must actually happen when a morning mist or fog rises from the ground to form clouds, although the water drops would be at a much less potential than 3×10^5 volts to the surrounding air.

Now supposing that these minute drops, still carrying a negative charge, are blown upwards into the cold upper atmosphere by an ascending air current, condensation takes place on the drops and by numerous collisions they eventually form large drops of the maximum size of 0·15 cm. radius. In doing this the area on which the charge is concentrated is reduced to a very small figure compared with the sum of the surface areas of all the minute drops composing it, for imagine a small drop of radius r to merge with another drop of the same radius to form a large drop of radius R. Then, assuming their shape to be spherical,

$$2\left(\frac{4}{3}\pi r^3\right) = \frac{4}{3}\pi R^3$$
$$2r^3 = R^3$$
or $$R = 2^{\frac{1}{3}}r$$
$$\therefore \frac{\text{Surface area of 2 drops, radius } r}{\text{Surface area of 1 drop, radius } R} = \frac{2 \times 4\pi r^2}{4\pi R^2}$$
$$= \frac{2r^2}{2^{\frac{2}{3}}r^2} = 2^{\frac{1}{3}} = 1\cdot26 \text{ approximately}$$

Hence if a small drop doubles its size, say 30 times, the area on which the charge is concentrated will be reduced to $\frac{\Sigma A}{(1\cdot26)^{30}}$, or approximately 1/1 000th of its original value, and, inversely, the potential will be increased to 1 000 times its original value.

The fact that lightning discharges are very often preceded or closely followed by an extra-heavy fall of rain seems to bear out this theory that the sudden rise in potential is associated with extra-heavy and sudden condensation.

This attempt to explain the concentration of charge in a thundercloud is put forward with the greatest reserve; I personally know of no experimental evidence to bear out the theory. However, it should not be difficult to prove its value in a well-equipped physical laboratory.

It is interesting to note that the above theory is contradictory to the theory of electrification suggested by Sir George Simpson, because it implies that the positive charge found on water drops, after breaking up larger drops, would disappear on reuniting the small drops to form drops of the original size.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT GLASGOW, NEWCASTLE, BELFAST, MANCHESTER, BIRMINGHAM, LOUGHBOROUGH, BRISTOL, AND MIDDLESBROUGH†

Prof. B. L. Goodlet (*in reply*):
Glasgow
In reply to Prof. Say I would state that the bursting effects of a lightning flash cannot be accounted for satisfactorily on the hypothesis of steam generation. Corona produces considerable attenuation and distortion of the travelling waves set up by a lightning stroke, but can hardly influence the initial voltage except by the effect mentioned in the paper. The damage referred to

by Mr. Collyns is probably due to the transfer of a surge through the transformer windings in the manner recently discussed by Dr. Allibone.*

Mr. Eccles's remarks are in part answered by Prof. Wilson. I do not think that an " earth wire " raised to a high positive potential would be popular, although the idea is interesting.

In the case mentioned by Mr. Erskine I imagine that the pole was shattered by a stroke to the line in its vicinity and that a travelling wave, chopped by the breakdown of the pole, was sent down the line. The oscillations in a transformer winding due to such impulses are discussed in Dr. Allibone's paper mentioned above.

I should like to know how Mr. Butler discriminates between direct and induced strokes. In many undertakings it would seem that a stroke is direct when its marks can be found, and induced when marks are not noticed. On an 11-kV line it is probably inevitable that most direct strokes should produce flashovers. There are, however, many cases of strokes having fallen very close to lines without causing any trouble, so that the induced-stroke hypothesis should not be accepted too lightly. Induced strokes were omitted from the paper as they have been discussed *ad nauseam* elsewhere.

In regard to fuse-blowing I can only say that a fuse does not blow unless current flows through it, and the path of this current must be traced. If the transformer reacted as a dead short-circuit on the end of the spur line, the current in the surge would be some 2 to 4 amperes per kilovolt of surge voltage. Earth wires under the power conductor may prevent the latter from falling on cows but cannot intercept lightning strokes.

In reply to Mr. Babb I can only say that if technical requirements and official regulations conflict, both cannot be satisfied. A trickle of water will reduce the 50-cycle sparking voltage, but will have much less effect on the impulse sparking voltage.

Newcastle

In reply to Mr. Winfield I would say that the relative value of a second earth wire and a counterpoise on the grid lines depends entirely on whether operating records indicate that improved stroke interception or lower footing resistance is required. I imagine that the former is probably more necessary.

Mr. Dickinson is referred to my reply to Prof. Say; I do not see how his theory can explain the shattering of non-hygroscopic substances.

Mr. Dunn should distinguish between the direction of movement of positive or negative charges and the direction of propagation of a state of ionization. As an analogy I might mention the case of an elastic rod struck at one end; the stress wave always travels away from that end, but the direction of motion of the particles is in the same direction as the wave only if the stress is compressive.

Mr. Ryle takes me to task for having neglected tower surge impedance in calculating surge voltages. My excuse is that, having indicated in Section 2(b) how this factor might be included, I subsequently ignored it for simplicity. I agree that if footing resistances are very low or towers very high, the waves up and down the

tower itself are decisive—but not, I think, in the average case. If Mr. Ryle's paper (No. 307) presented to the 1937 Conference on Large High-Tension Systems is the result of my omission, I consider it a fortunate one.

In reply to Mr. Leyburn I would say that the effectiveness of interception by the earth wires of the grid must be settled by experience.

Belfast

In reply to Mr. Blair I would say that I doubt whether copper earth-wires would afford better protection than steel ones.

The protective action of short lengths of cable, about which Mr. Christie asks, has been studied by K. B. McEachron, J. G. Hemstreet, and H. P. Seelye.*

Mr. Cooper is referred to the Royal Society papers by Prof. Schonland and his collaborators.

The practice referred to by Mr. Johnston may be associated with the darkness usual during storms; I can think of no other rational reason.

Mr. Partridge's experiences are interesting. I imagine that the wired poles were not shattered because a high voltage could not build up along such a pole. I cannot explain the fusing of the wires.

Mr. Robins is referred to my reply to the London discussion (vol. 81, page 55).

Mr. Scott's energy calculations would be even more impressive if he took into account the energy set free by the condensation of 65 000 tons of water from vapour.

Manchester

Dr. Miller's remarks are, as usual, most interesting.

I would inform Mr. Fennell that " tropopause " is the term used to denote the lower boundary of the stratosphere or outer isothermal region of the atmosphere. I believe that Thyrite is a good material, but I must add that I was until recently connected with its makers.

In reply to Mr. Thompson I would say that the field below the cloud depends less upon the contour of the ground than upon the space-charge above it. Free electrons in the atmosphere do not normally exist; the ions (which Mr. Thompson probably has in mind) move with a *velocity* proportional to the field strength. For the remaining points I would refer him to Prof. Schonland's papers.

Mr. Mallinson's experience is most interesting.

Mr. Miranda's experiments are most valuable and I hope that they will be continued.

Birmingham

I am afraid that I cannot follow Major Taylor's reasoning on the safety of the Boulder Dam lines. Greater spacing between the two lines would increase the probability of *one* of them being under a storm; 100 yards is sufficient to prevent trouble from spreading. The lines are sectionalized in order to secure adequate stability of synchronization.

Mr. Sumner's remarks are both interesting and valuable. It is a pity that more operating engineers do not proceed in the same systematic manner. An earth wire

is almost useless unless it intercepts strokes which otherwise would fall on the line wires. It may be useless even if it does intercept these strokes, if the potential it assumes to earth (due to high footing resistances) is greater than the insulation of the line can withstand.

The flash about which Messrs. Onley and Halliday ask was travelling towards the camera.

Loughborough

In reply to Mr. Tucker I would point out that not every overhead earth-wire is properly designed and mounted.

In reply to Mr. Brookes I would say that I cannot conceive of a streamer consisting solely of charge carriers of one sign. The multiplication of potential by the coalescence of drops does not occur when a large number of drops are present. The second leader stroke in the multiple flash is an experimental fact and it is therefore necessary to consider it.

Mr. Nixon seems to think that lightning damage on a line results only from the follow-up current of power frequency, but there are many cases of insulators having been damaged when the lines were dead. Surge voltages in transformer windings are dealt with in Dr. Allibone's paper mentioned previously; and I have referred to the protective action of short lengths of cable in my reply to Mr. Christie in the Belfast discussion.

The earthing relay mentioned by Mr. Woods might help matters in the case of a multiple stroke of long duration, but I would consider it a very doubtful investment.

For information on the duration of ionized lightning channels Mr. Bentley is referred to Prof. Schonland's paper.

I cannot explain the occurrence described by Mr. Pierce, but many similar instances are on record.

Bristol

Prof. Robertson's criticisms of Fig. 2 and 3 are justified; the arrows in the latter diagram are intended to indicate the circuital nature of the current. The pressure of the steam generated by the heat of the current is not sufficient to explain the bursting of materials which do not contain moisture. I agree that a separate earth for the lightning rod is essential.

Mr. Mackay's initial remarks are interesting, but I am unable to follow his reasoning on the method of protection he advocates. I cannot see that such a construction will result in any material benefit.

Middlesbrough

In reply to Mr. George I would say that it appears to be established that the final connection to the stepped leader stroke is made by streamers rising up from the ground. I do not think that earth resistance has any effect on the number of strokes per flash; this is settled by conditions in the cloud.

Mr. Gibson has obviously considered the whole subject very thoroughly and his contribution is most interesting. I cannot reply to all his questions, some of which I think can only be answered by the careful collection and sifting of field records. I do not think that there is any appreciable potential gradient in the earth under steady conditions; when, however, the field is changing it is possible (as Stekolnikov has suggested) that its configuration is determined largely by the contour of the underlying strata. Underground water is widely believed to attract lightning strokes. The examples of induced trouble quoted are particularly interesting; in many instances strokes falling close to a line produce no disturbance whatsoever, so that there is undoubtedly much to be learnt on this matter.

THE REFLECTION COEFFICIENT OF THE EARTH'S SURFACE FOR RADIO WAVES*

By J. S. McPETRIE, Ph.D., B.Sc., Associate Member.

[From the National Physical Laboratory.]

SUMMARY

Curves are given from which, by two interpolations, the reflection coefficient of the ground can be determined for any angle of incidence or any value of dielectric constant and conductivity of that surface. Curves are given for the two cases in which the electric vector of the incident radiation is polarized in and perpendicular to the plane of incidence respectively, so that the reflection coefficient can also be determined for any state of polarization.

INTRODUCTION

The solution of many of the problems relating to the propagation of radio waves necessitates a knowledge of the magnitude of the reflection occurring at the earth's surface. For frequencies within the visible spectrum the distance of any object or receiver from a reflecting surface is so great compared with the wavelength of the radiation that at the point at which reflection occurs the incident radiation may be assumed to be plane. The reflection occurring under such conditions is given by the well-known Fresnel equations. In the case of the propagation of radio waves along the earth's surface, however, the distance between the transmitter or receiver and that surface may be very small compared with the wavelength. The radiation incident on the earth's surface is then no longer plane, and care must be taken in the application of the results obtained from the simple ray theory.

The conditions required for the ray theory to apply may be stated roughly as follows:—

(1) If the radiation incident on the earth's surface (or any other reflector) is polarized so that the electric vector is perpendicular to the plane of incidence, the ray theory may be applied for practically all heights of the receiver or transmitter, provided the effects of refraction in the atmosphere and diffraction round the earth's surface may be neglected.

(2) If the radiation is polarized with the electric vector in the plane of incidence, the ray theory applies only to cases in which either or both the transmitter and the receiver are at heights above the earth comparable with the wavelength. This limitation to the applicability of Fresnel's equations occurs because (as was first shown by Sommerfeld†), for this type of polarization, a wave,

usually known as the surface wave,† is propagated along the earth's surface and the formula for the propagation of this wave is not deducible from the ordinary ray theory. For high angles of incidence or elevated transmitter and receiver, Fresnel's equation can still be used as the surface wave is confined to regions near the ground.

Even with the above limitation to the applicability of the ray theory, the reflection coefficient of the ground as determined from the theory is often required in radio problems. Fresnel's equations in their usual form are such, however, that the calculation of the reflection coefficient, which at best is laborious, must be made for each particular problem. It is shown in this paper‡ how, by a series of interpolations, the reflection coefficient of the ground can readily be determined without recourse to computation for all angles of incidence, all states of polarization of the incident radiation, and all values of ground constants, met with in practice.

DESCRIPTION OF METHOD

The reflection coefficient at the earth's surface is complex and may conveniently be represented in the form $(K + jK')$. The magnitudes of the two rectangular components K and K' are functions of the dielectric constant (κ), the ratio of the conductivity of the ground (σ) to the frequency (f) of the radiation considered, and also of the angle of incidence. The reflection coefficient is also a function of the state of polarization of the radiation incident on the earth's surface. This latter complication is readily overcome by resolving the radiation into its respective components polarized in and perpendicular to the plane of incidence. In this paper, the reflection coefficient has been calculated for these two states of polarization.

The usual method for determining the reflection coefficient for a particular case is to calculate from Fresnel's equations the two rectangular components of the coefficient for the appropriate values of the dielectric constant and of the ratio of conductivity to frequency. As the effects of these two functions on the coefficient are difficult to assess separately, a series of values of both must be taken in order to determine possible limits in the value of the reflection coefficient. For the general

determination of the reflection coefficient it is much more convenient to make the calculation assuming κ as constant and the ratio σ/f as parameter in turn. When such a calculation is made for a given angle of incidence a series of interesting curves can be drawn as shown in Fig. 1. In this figure the horizontal axis represents the in-phase component K, and the vertical axis the in-quadrature component K', of the reflection coefficient. The point of intersection of any two curves determines both K and K', so that the length of the vector to the point of intersection gives the magnitude of the reflection coefficient and the angle which it makes with the horizontal axis gives the change of phase occurring on reflection, for the ground constants represented by the common values of κ and σ/f of the intersecting curves. The reflection coefficient for the same angle of incidence for any values of k and σ/f not given directly by the curves in Fig. 1 can be obtained by interpolation. If a series of curves such as those in Fig. 1 are calculated for a sufficient number of angles of incidence, the reflection coefficient for any values of κ and σ/f can be obtained by a second interpolation for all angles of incidence.
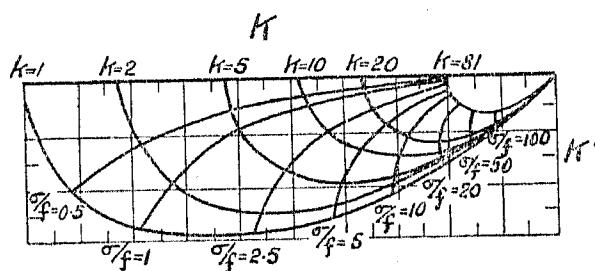
Fig. 1.—Curves giving the in-phase (K) and the in-quadrature (K') components of the reflection coefficient for a given angle of incidence and various values of the ground constants.

This method has been followed in the paper for the two cases of radiation polarized respectively in and perpendicular to the plane of incidence. By resolving the polarization of the incident radiation into these two components, therefore, the reflection coefficient can be found for any values of ground constants or angles of incidence; conversely, if in any problem the reflection coefficient and phase-change on reflection are known, the ground constants can be determined directly from the curves. The curves are instructive also in showing the different effects of change in dielectric constant or conductivity of the reflecting surface. The values of dielectric constant have been limited to those between 1 and 81, the latter representing the conditions for water. No values for ionized media ($\kappa < 1$) have been included, as the present study is limited to reflection from the earth's surface.

RADIATION POLARIZED WITH ELECTRIC FIELD PERPENDICULAR TO PLANE OF INCIDENCE

If the reflection coefficient for horizontally-polarized waves is designated $(K_p + jK_p')$, the values of K_p and K_p' are given by

$$K_p = \frac{\cos^2\theta - (c^2 + d^2)}{\cos^2\theta + (c^2 + d^2) + 2c\cos\theta} \quad . \quad (1)$$

$$K_p' = \frac{-2d\cos\theta}{\cos^2\theta + (c^2 + d^2) + 2c\cos\theta} \quad . \quad (2)$$

in which θ (the angle of incidence on the ground) and c and d are given by

$$c = +\frac{1}{\sqrt{2}}\sqrt{\left\{\sqrt{\left[(\kappa - \sin^2\theta)^2 + 4\frac{\sigma^2}{f^2}\right]} + (\kappa - \sin^2\theta)\right\}} \quad (3)$$

$$d = -\frac{1}{\sqrt{2}}\sqrt{\left\{\sqrt{\left[(\kappa - \sin^2\theta)^2 + 4\frac{\sigma^2}{f^2}\right]} - (\kappa - \sin^2\theta)\right\}} \quad (4)$$

where κ represents the dielectric constant of the ground, σ the conductivity in electrostatic units, and f the frequency of the radiation.

The positive direction of the reflected wave as given by equations (1) and (2) is assumed (as shown in Fig. 2) to be the same as that of the primary radiation.

Equations (1) and (2) have been used, in the manner described in the previous Section, to obtain the curves given in Fig. 3, representing the reflection coefficient for angles of incidence of 0°, 20°, 40°, 50°, 60°, 70°, and 80° respectively. It will be seen that for given ground-constants the reflection coefficient increases as the angle of incidence increases, becoming unity for all ground
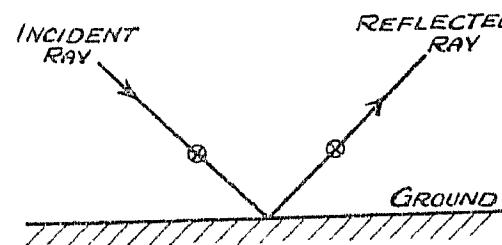
Fig. 2.—Diagram showing relative directions of electric field in incident and reflected rays for cases given in Fig. 3.

constants for an angle of incidence of 90°. As the vector representing the reflection coefficient lies in the second quadrant, there must be an advance of phase on reflection of between 90° and 180° for horizontally-polarized waves.

RADIATION POLARIZED WITH ELECTRIC FIELD IN PLANE OF INCIDENCE

For this type of polarization the components K_i and K_i' of the reflection coefficient $(K_i + jK_i')$ are given by

$$K_i = \frac{\left(\kappa^2 + 4\frac{\sigma^2}{f^2}\right)\cos^2\theta - (c^2 + d^2)}{\left(\kappa^2 + 4\frac{\sigma^2}{f^2}\right)\cos^2\theta + (c^2 + d^2) + 2\cos\theta\left(\kappa c - 2d\frac{\sigma}{f}\right)} \quad (5)$$

$$K_i' = \frac{-2\cos\theta\left(\kappa d + 2c\frac{\sigma}{f}\right)}{\left(\kappa^2 + 4\frac{\sigma^2}{f^2}\right)\cos^2\theta + (c^2 + d^2) + 2\cos\theta\left(\kappa c - 2d\frac{\sigma}{f}\right)} \quad (6)$$

in which the symbols have the same significance as in equations (1) and (2). The positive direction of the electric field in this case is shown in Fig. 5. The curves given in Fig. 4 have been calculated for angles of incidence of 0°, 20°, 40°, 50°, 60°, 70°, and 80°. It will be seen that for zero angle of incidence the reflection
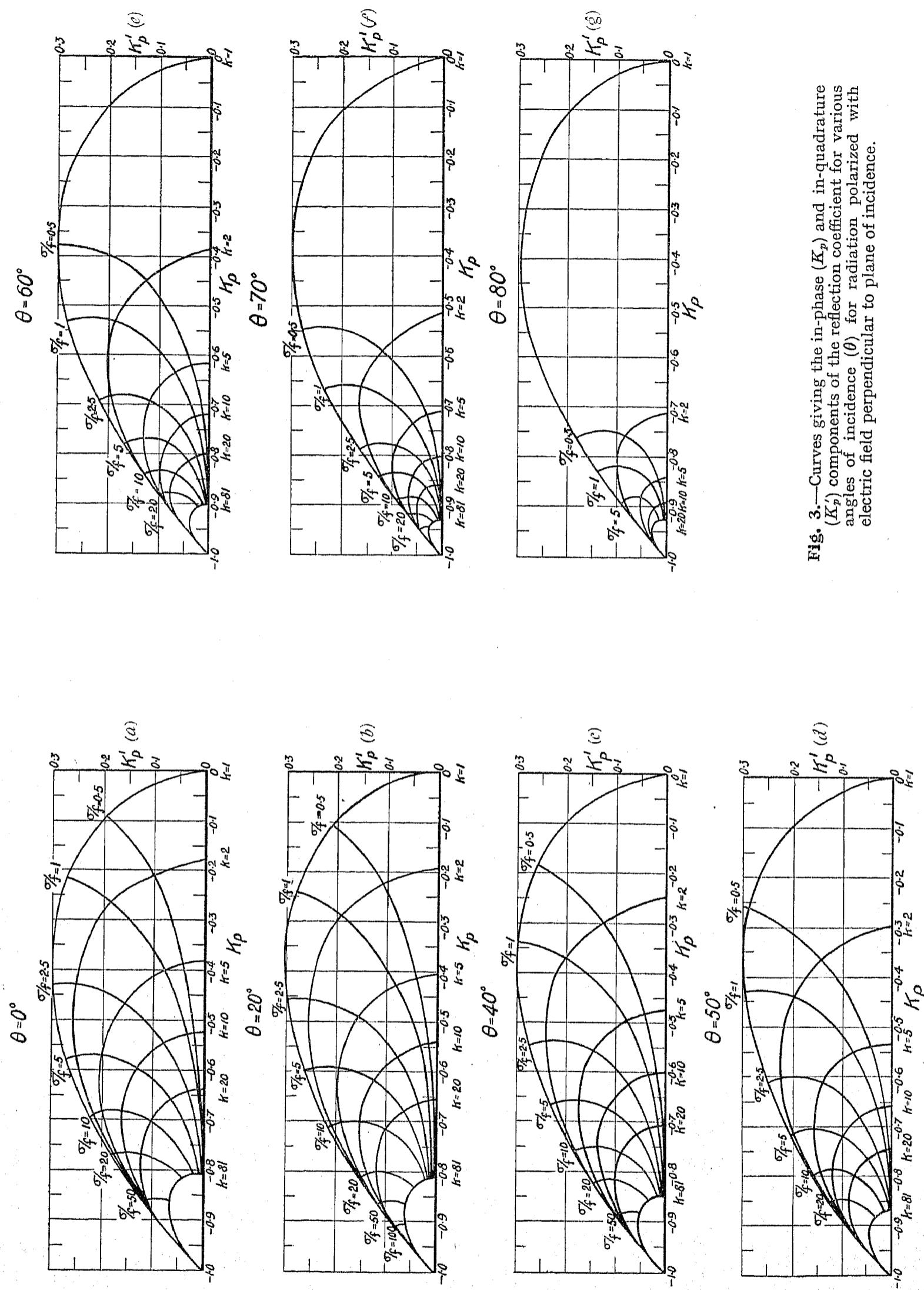
Fig. 3.—Curves giving the in-phase (K_p) and in-quadrature (K_p') components of the reflection coefficient for various angles of incidence (θ) for radiation polarized with electric field perpendicular to plane of incidence.
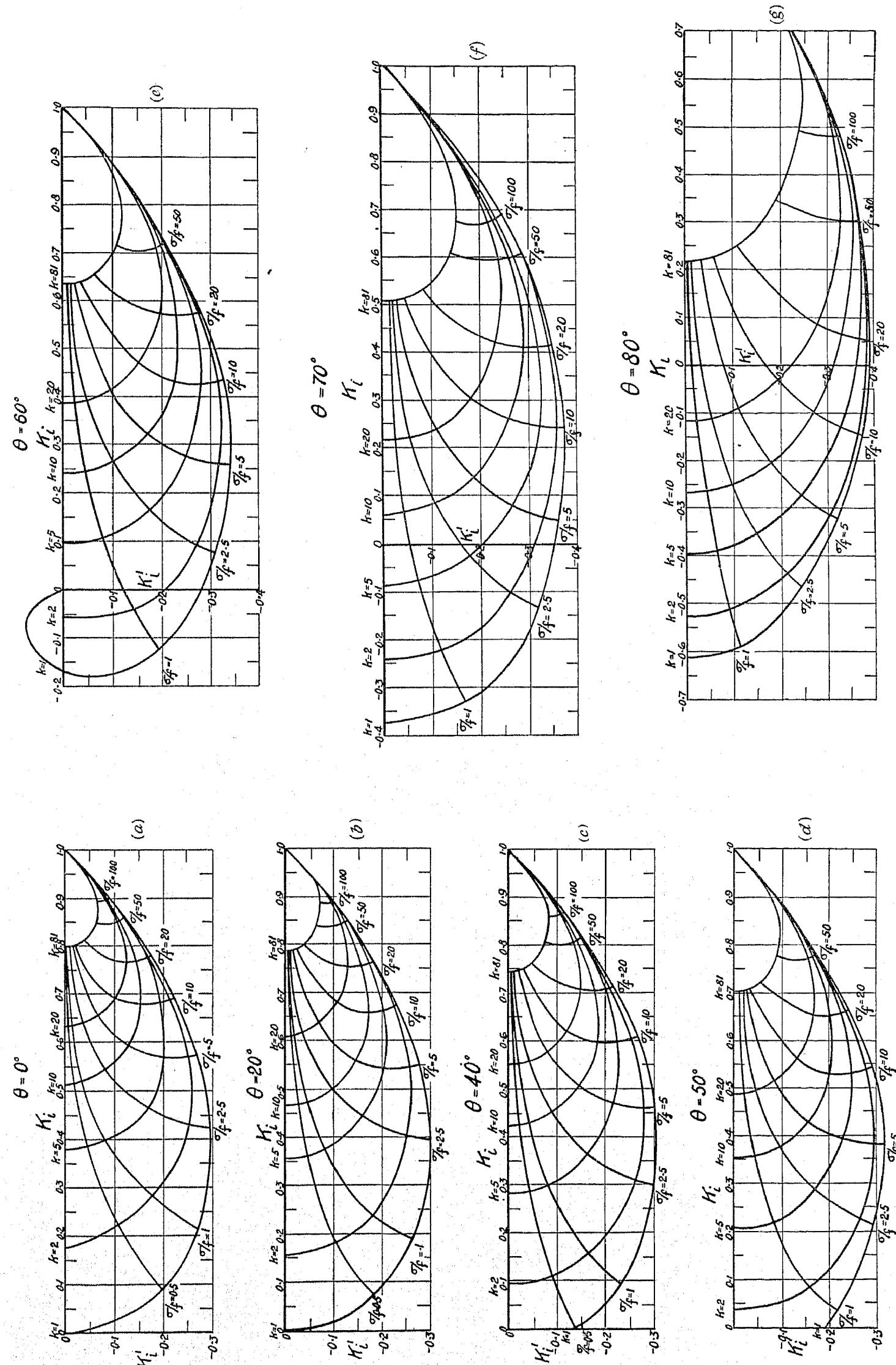
Fig. 4.—Curves giving the in-phase (K_i) and in-quadrature (K_i') components of the reflection coefficient for various angles of incidence (θ) for radiation polarized with electric field in plane of incidence.

coefficient has the same magnitude as for horizontally-polarized waves at the same angle, but that there is a change in phase of 180° between the two cases. The reflection coefficient should be identical for this case of normal incidence, and the apparent discrepancy arises from the assumption as to the positive direction of the reflected waves as given in Figs. 2 and 5. It will be seen that, as with horizontally-polarized waves, the reflection coefficient tends to unity as the angle of incidence approaches 90°. The reflection coefficient of a body having zero conductivity and unity dielectric constant is zero for all angles of incidence. The curve for this value of dielectric constant is similar to that for the other values of dielectric constant until the reflection coefficient lies in the third quadrant. When this occurs the curve for unit dielectric constant does not terminate on the axis of abscissae but crosses it into the second quadrant and spirals back in that quadrant to the origin. This part of the curve is limited to small

Fig. 5.—Diagram showing relative directions of electric field in incident and reflected rays for cases given in Fig. 4.

conductivities and, as it is of no practical importance in the present problem, it has not been included in any of the diagrams, except Fig. 4(e); here it is given only to show the result obtained with such a reflector.

EXAMPLES OF USE OF METHOD

The curves given in the paper may be used in two ways: firstly, to find the reflection coefficient at any angle of incidence when the ground constants are known; or, secondly, to determine the ground constants if the reflection coefficient is known. As an example of the use of the first method, suppose the reflection coefficient and phase-change on reflection are required for vertically-polarized waves at a frequency 4×10^6 cycles per sec. for an angle of incidence of 45°, the dielectric constant and conductivity of the ground being respectively 15 and 10^8 e.s.u.* The appropriate value of σ/f is, therefore, 25. Reference to Fig. 4(d) shows that the values of

* The electrical constants of different types of ground surface at radio frequencies have been determined by R. L. Smith-Rose (*Journal I.E.E.*, 1934, vol. 75, p. 221). His paper also includes an extensive bibliography on the subject.

K_i and K'_i for the given values of κ and σ/f are approximately 0.735 and -0.16 respectively for an angle of incidence of 40°, while Fig. 4(e) shows them to be 0.685 and -0.18 for an angle of incidence of 50°. Assuming that the rate of change of both components is approximately linear over the range 40° to 50°, the values at an angle of incidence of 45° become 0.71 and -0.17. These values represent, therefore, the two components of the reflection coefficient, giving 0.73 for the magnitude of the coefficient and $-13°$ for the phase-change. The coefficient could, of course, have been determined without resolving it into its two components. The actual method adopted depends to a large extent on personal preference. Calculating the magnitudes of K_i and K'_i directly from equations (5) and (6) gives the same values for K and K_i, so that the accuracy of the method of interpolation in the particular example given is amply sufficient.

If the reflection coefficient were given as 0.73 and the phase-change as $-13°$ for an angle of incidence of 45°, the ground constants could be determined by reversing the above procedure.

An example of the application of the method to the determination of the electrical constants of the ground from an experimental determination of the reflection coefficient at normal incidence has already been given by the author.*

CONCLUSIONS

The curves given in the paper enable the reflection coefficient for any angle of incidence, any state of polarization of the radiation, and any electrical constants of the ground, to be determined by, at most, two interpolations; conversely, the ground constants can be found from the curves if the reflection coefficient and phase-change on reflection are known for any angle of incidence at the earth's surface. In addition, the curves are instructive in that they show how small changes in dielectric constant or conductivity affect the reflection conditions for any angle of incidence.

ACKNOWLEDGMENTS

* *Proceedings of the Physical Society*, 1934, vol. 46, p. 637.

DISCUSSION ON
"THE APPARENT INTER-ELECTRODE CAPACITANCE OF A PLANAR DIODE"*

Mr. W. E. Benham (*communicated*): The author's contribution to the theory of valve circuits is directed towards explaining the variations in hot capacitance in a diode valve as a function of the space current. In Section (1), he says that he is not aware that experimentally the anode capacitance is a continuous function of the anode current. If he will refer to pages 482–489 of my paper in the *Philosophical Magazine* (1931, vol. 11) he will, however, find that such is the case. A resonance method was used for measurements on diode capacitances, in view of the exceptionally heavy damping. As I had succeeded in measuring diode capacitances by this method, though not without some difficulty, the same method was used for experiments on triodes. A more accurate method was adopted at a later date for triode capacitances, but my published measurements using a resonance method may be taken as accurate to $0 \cdot 1$ $\mu\mu$F and give some general indication of the effects studied. It should be mentioned that ΔC changes from negative to positive in a diode as emission limitation sets in. Fig. 13 of my paper does not show this effect, as the region investigated corresponds to infra-saturation. A number of curves taken in 1928 did, however, show the effect, also ΔC_{fg} was found to be negative for a temperature-limited triode. For various reasons these results were not published at the time, but they now receive confirmation in the light of North's and of Bakker and de Vries's[†] extensions of Müller's theory.[‡] In regard to the ideal theoretical value of 3/5, on page 487 I pointed out that this value was only intended to apply at one point of the characteristic. Fig. A shows a typical diode characteristic and also the ideal 3/2 power law. The point where the analysis neglecting initial velocities approaches reality is indicated by a cross and may be referred to as the Langmuir point. Müller[§] has dealt with the region to the right of the Langmuir point and his analysis gives, inter alia, variations of capacitance in this region. The d.c. results given by Mr. Moullin in the Appendix will be of value in providing quantitative interpretation of Müller's important work, as also will the work of R. Cockburn (in course of publication).[||] The region to the left of the Langmuir point can only be exactly explained by a very complete investigation of the potential minimum. I am not in agreement with Mr. Moullin that equations (1) and (2) of his paper are well known, nor do I think we can employ them here. Fig. 1 and equation (1) show an infinity in ρ which is, of course, purely mythical, since the electron velocity at O is not

zero. On page 671 Mr. Moullin uses the symbol b for something quite different from its meaning on page 668. This makes his analysis very confusing. His conclusion in Section (6), to the effect that the displacement current at the potential minimum is nearly equal to that at the anode, is at variance with the views I expressed in a recent paper.[†] My view still is that the displacement current is zero (or very small) at the mean position of the potential minimum, but that the alternating current at the cathode consists of some displacement current, plus convection current arising from electrons returning from the potential minimum. No alternating convection current is carried by *outgoing* electrons at infinitesimal distance from the cathode, owing to the inability of the
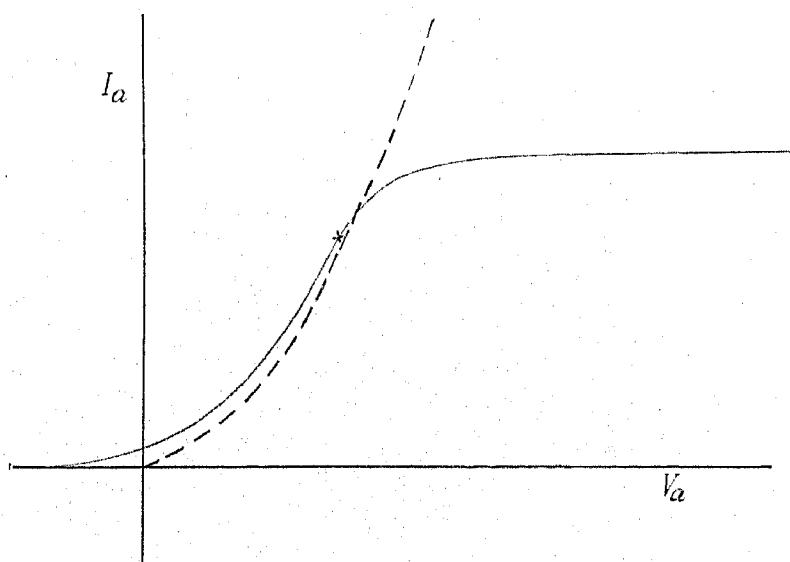
Fig. A

electrons (in view of their inertia) to respond instantaneously to the alternating field in which they find themselves immediately on emerging from the cathode. These 1934 views do not conflict with my 1928/31 assumption that the convection current at the cathode was equal to the total current, since this hypothesis merely corresponded to assuming that the potential minimum coincided with the cathode. In the space-charge limited diode, the electric field undergoes a much greater change (for a given anode potential) as we pass from cathode to anode, than in a space-charge saturated condition, and the hot capacitance would therefore be expected to differ somewhat from that given by simple theory.

Mr. E. B. Moullin (*in reply*): Surely equations (1) and (2) are extremely well known: they follow directly from any solution of the space-charge-limited condition in which electrons cross the barrier with zero velocity. I agree they cannot be accepted: this long and laborious paper

* Paper by Mr. E. B. MOULLIN (see vol. 81, page 667).
† C. J. BAKKER and G. DE VRIES: *Physica*, 1935, vol. 2, p. 683. D. O. NORTH: *Proceedings of the Institute of Radio Engineers*, 1936, vol. 24, p. 108.
‡ JOHANNES MÜLLER: *Hochfrequenztechnik und Elektroakustik*, 1933, vol. 41, p. 156.
§ *Loc. cit.*
|| See also *Proceedings of the Physical Society*, 1935, vol. 47, p. 810.

† See also *Proceedings o the Physical Society*, 1935, vol. 47, p. 8.

has been written only because they cannot be accepted as representing a real diode in the problem investigated here. Surely this is made clear in Section (1) of the paper. I agree that it is unfortunate I have used the symbol b in the equation $i = I'(1 + bt)$ near the beginning of Section (5). If Mr. Benham will replace b where it appears in Section (5) up to and including equation (26) by b' I think all confusion will be avoided.

I am interested to know that Mr. Benham still considers the displacement current to be very small at the mean position of the barrier. The analysis of this problem is very complex and it is possible that I have taken some inappropriate boundary condition. The steps leading up to my conclusions in Section (6) are straightforward. I hope that Mr. Benham will later point out the place where I have taken the step which leads me to conclusions different from his, and that he will then discuss critically the validity or invalidity of it.

DISCUSSION ON
" THE DEPENDENCE OF THE INTER-ELECTRODE CAPACITANCES OF VALVES UPON THE OPERATING CONDITIONS "*

Mr. D. A. Bell (*communicated*): It seems probable that the author was not aware of a paper published in 1935† which reported work on the inter-electrode capacitances of valves carried out by me at Oxford University. It is very gratifying to find that those measurements, made with the simplest of apparatus, are generally confirmed by the complete range of accurate results obtained by the author at the National Physical Laboratory. The curves are of the same general shape, and two particular examples of measurements on identical types of valve may be quoted:—

(1) I found a value of $1 \cdot 0 \, \mu\mu\mathrm{F}$ as the limit of $\Delta(C_{fg} + C_{ag})$ for an LS5 valve at $V_a = 210$, whereas the author gives $1 \cdot 07 \, \mu\mu\mathrm{F}$ for the maximum change at $V_a = 150$.

(2) For an LS5b valve the two measurements are respectively $\Delta(C_{fg} + C_{ag}) = 1 \cdot 2 \, \mu\mu\mathrm{F}$ at $V_a = 223$, and $\Delta(C_{fg} + C_{ag}) = 0 \cdot 97 \, \mu\mu\mathrm{F}$ at $V_a = 150$.

The lack of exact constancy of capacitance-change for a fixed value of anode current was also illustrated in Fig. 3(*d*) of the earlier paper.

Perhaps the magnitude of the influence of filament temperature should be treated with more than the usual caution, despite the theoretical work of Moullin. For, referring to the curve for a DO24 valve in Fig. 4 of the present paper, it will be seen that above $I_f = 1 \cdot 74$, i.e. when space-charge limitation is presumably nearly complete, increasing the filament current still increases the capacitance-change only in proportion to the small growth of anode current, and shows no indication of a direct influence of temperature.

The main purpose of this communication is, however, to point out that rough results for $\Delta(C_{ag} + C_{af})$ were given in my paper; and to urge that, since results of at least qualitative significance were obtained with the crudest apparatus, experimental difficulties should not be allowed to delay the extension of accurate measurements on this important problem.

* Paper by Mr. T. IORWERTH JONES (see vol. 81, page 658).
† *Marconi Review*, 1935, No. 57, p. 18.

Mr. W. E. Benham (*communicated*): The author's measurements cover a large variety of valve types, and the form in which results are drawn up will appeal to those engaged in circuit design. One might perhaps have wished for a larger proportion of measurements on indirectly-heated cathode valves, as these are of particular interest in connection with mains-operated equipment.

It would, I think, have enhanced the value of the results somewhat if an indication had been given of the grid bias corresponding to the various anode currents. The point of particular interest is that corresponding to the incidence of grid current.

In Section (2)(*b*), referring to the arrangement of Fig. 2, the author points out that filament and grid are at the same alternating potential. This alternating potential is substantially zero (filament connected to screen), so that we have under consideration the value of C_{ag} under conditions for which the anode is alternating in potential, and the grid sensibly constant in potential. This condition has not hitherto received mathematical treatment, but in view of the obvious convenience of this method of measurement a brief analysis is given below.

We may conveniently begin with the appropriate " admittance theorem,"* writing, for the first-order admittance between grid and anode [assuming the displacement current $(i - i_c)$ all flows to the grid,

$$ Y_{ga} = \frac{i - i_c}{v_a} = pC_{ga} + \frac{i_e - i_c}{v_a} \qquad . \quad . \quad (1) $$

where $p = \omega\sqrt{(-1)}$.

Here i represents the total alternating current passing between grid and anode, i_c the electron convection current at the anode (i.e. at the electrode where the alternating potential is applied), and v_a the alternating potential at the anode. The grid is assumed at zero (a.c.) potential, and the bias does not enter explicitly

* See W. E. BENHAM: *Wireless Engineer*, 1936, vol. 13, p. 406.

into the calculation. The current $\bar{\imath}$ is composed of the "cold" displacement current ($pC_{ga}v_a$) and the induced current i_e, being that current flowing (in the external circuit) which is derivable from the electron convection current i_c by means of an instantaneous space-averaging process over all values i_c' of i_c between grid and anode.

A knowledge of i_e and i_c sufficiently exact for purposes of illustration is obtained in the following manner. First of all, there is a small alternating potential acting on the filament-grid region, given (nearly) by v_a/μ. This voltage may be regarded as the anode-potential fluctuation transferred to the "diode equivalent surface" lying just beyond the grid.* Here we shall take the potential v_a/μ to act at a surface coinciding with the grid, and so obtain

$$(i_c)_g = g_m v_g = g_m \frac{v_a}{\mu} = \frac{v_a}{R_a} \qquad . \qquad . \qquad (2)$$

The neglect here of finite electron transit-time in the filament-grid space can be shown to be without effect on the hot value, $\overline{C}_{ga}$, of C_{ga}. It is, however, necessary (at all frequencies) to include the effect in the grid-anode space. Thus, at any surface between grid and anode,†

$$i_c' = (i_c)_g e^{-p\tau_0'} - I_a \frac{\partial \tau_1'}{\partial t} = (i_c)_g e^{-p\tau_0'} - I_a \cdot p\tau_1' \quad . \quad (3)$$

where τ_0', τ_1', are respectively the d.c. and fluctuating components of electron transit-time (being that interval between the instant the electrons pass the diode equivalent surface and the instant at which the electrons reach the assumed surface). A value for $p\tau_1$ corresponding to negligible space-charge between grid and anode will be assumed for simplicity, and, since the term ($-I_a \cdot p\tau_1$) is small in most practical cases, we will give $p\tau_1$ the approximate value corresponding to a temperature-limited planar diode, namely (putting $V_{ag} = V_a - V_g \simeq V_a$),

$$p\tau_1' = -\frac{p\tau_0'}{2} \cdot \Upsilon_3(p\tau_0') \cdot \frac{v_a''}{V_a''}$$

where $\dfrac{v_a''}{V_a''} = \dfrac{v_a}{V_a}$ (nearly) and $\Upsilon_3 = \left(1 - \dfrac{2}{3}p\tau_0'\right)$ to sufficient accuracy for present purposes. This gives for (3), using (2),

$$i_c' \simeq \frac{v_a}{R_a}(1 - p\tau_0') + \frac{p\tau_0'}{2}I_a\frac{v_a}{V_a} \quad . \quad . \quad . \quad (4)$$

To obtain i_e we require an instantaneous integration with respect to $x' \left(= \dfrac{dx'}{d\tau_0'}d\tau_0' \right)$, and after integration between grid and anode has been effected we divide by the grid-anode distance x_{ag}. It is sufficient, to our present degree of approximation, to take

$$\frac{dx'}{d\tau_0'} = \gamma\tau_0'; \quad x_{ag} = \tfrac{1}{2}\gamma\tau_0^2$$

in which γ is the acceleration (constant on our hypothesis of neglect of space charge) in the grid-anode space. We thus multiply (4) by $2\tau_0'/\tau_0^2$ and integrate with respect

to τ_0' between the limits $\tau_0' = 0$ and $\tau_0' = \tau_0$; obtaining, for the induced current,

$$i_e \simeq \frac{v_a}{R_a}\left(1 - \frac{2}{3}p\tau_0\right) + \frac{p\tau_0}{3}I_a\frac{v_a}{V_a} \qquad . \qquad . \qquad (5)$$

We now drop the primes from equation (4) and subtract the resulting equation from equation (5). This gives ($i_e - i_c$) for insertion in equation (1). Thus

$$Y_{ga} \simeq p\left(C_{ga} + \frac{\tau_0}{3R_a} - \frac{I_a\tau_0}{6V_a}\right) \qquad . \qquad . \qquad (6)$$

If $\overline{C}_{ga}$ denote the hot value of C_{ga}, we have for $(\overline{C}_{ga} - C_{ga})$ the value

$$\delta C_{ga} = \frac{\tau_0}{6}\left(\frac{2}{R_a} - \frac{I_a}{V_a}\right) = g_m\frac{\tau_0}{6}\left(\frac{2}{\mu} - \frac{I_aR_a}{V_a\mu}\right) \quad . \quad (7)$$

The value of δC_{ag} given by equation (7) is exceedingly small, and positive. Owing to approximations made in derivation, we cannot be sure that the true value of δC_{ga} would come out positive, but we can be sure that it will remain exceedingly small. When, however, we come to consider the case where the grid electrode fluctuates in potential, the anode and filament being at constant potential, a comparatively large value of ΔC_{ga} is predicted. This case has been studied in detail by North,* but a more simple treatment is outlined below in order to show how this case differs from that examined above. Equation (1) must be replaced by the slightly different equation

$$Y_{ga} = pC_{ga} + \frac{i_e - (i_c)_g}{-v_g}$$

in which we note that i_c must now be reckoned at the grid (i.e. where the alternating potential is applied) and also that a negative half-cycle of v_g corresponds to a positive half-cycle of grid-anode potential. The remaining equations (2a) to (5a) would be similar, but with v_a replaced by ($-v_g$); so we remark simply that now we must take

$$i_e - (i_c)_g = i_e - g_m(+v_g)$$
$$= g_m v_g\left(1 - \frac{2}{3}p\tau_0\right) + \frac{p\tau_0}{3}I_a\frac{(-v_g)}{V_a} - g_m(+v_g)$$
$$\therefore \quad \frac{i_e - (i_c)_g}{-v_g} = \frac{2}{3}p\tau_0\left(g_m + \frac{I_a}{2V_a}\right)$$

For the change in capacitance we now write ΔC_{ga}, which comes to

$$\Delta C_{ga} = \frac{g_m\tau_0}{3}\left(2 + \frac{I_aR_a}{V_a\mu}\right) \qquad . \qquad . \qquad (7a)$$

The second term is exceedingly small, and equations (7) and (7a) give

$$\Delta C_{ga} - \delta C_{ga} = \frac{2}{3}g_m\tau_0 \qquad . \qquad . \qquad . \qquad (8)$$

$$\simeq \frac{4}{3}C_{fg}\frac{\tau_{ga}}{\tau_{fg}} \qquad . \qquad . \qquad . \qquad . \qquad (8a)$$

Equation (8) may be shown to be more accurate than the rest of the analysis; this arises from the fact that

* The electrostatics of triodes is discussed in a forthcoming paper in the *Proceedings* of the Institute of Radio Engineers; and in greater detail, in Prof. Dow's new book "The Fundamentals of Engineering Electronics" (John Wiley, and Chapman and Hall).
† Primes indicate that the formula applies to any surface: when it is applied later to the anode the primes will be dropped.

* D. O. North: *Proceedings of the Institute of Radio Engineers*, 1936, vol. 24, p. 123.

the " exceedingly small " terms of equations (7) and (7a) are exactly equal, corresponding as they do to " variation time " effects in the grid-anode space.

This brings us to the interesting point that the inter-electrode capacitances are influenced to a different extent depending upon which electrodes are earthed and which are subject to alternating potentials. As is pointed out in the author's Reference (2),* " The same electrons which increase the capacity between cathode and negative grid can decrease the capacity between cathode and positive anode."

A small point arises in regard to the " hot " value of C_{af}. The cold value will have been balanced out, in the circuit of Fig. 2, by the use of a screened resistance box across the right-hand arm of the Wagner earthing device. As I understand the measurement, however, it would not be possible to balance out δC_{af} as well. One might light the filament and leave the grid floating, but then the grid would rapidly acquire a more negative potential by accumulation of electrons and there would be negligible change in C_{af}. I should like to inquire whether, referring to Section (2)(b), the author considers that δC_{af} was balanced out. It is just possible that δC_{af} is sufficiently negative to change the apparent value of δC_{ag} from slightly positive [equation (7)] to slightly negative. This would account for the negative value of ΔC_{ag} shown in Fig. 6.

In regard to Section (4)(c), it is to be noted that when V_a is increased τ_{ga} decreases somewhat more rapidly than g_m increases. The measurements are thus at least qualitatively in agreement with formulae (7) or (7a), assuming C_{fg} remains unchanged. The magnitude of the effect is such as to indicate that equation (7a) would be preferable.

Electron optical effects are likely to be of some

* W. E. BENHAM: *Philosophical Magazine*, 1931, vol. 11, p. 489.

importance in influencing inter-electrode capacitance variations,* and these are difficult to handle in this connection.

Mr. T. I. Jones (*in reply*): It is encouraging that the publication of this paper should have brought forth contributions to the discussion of the subject from two workers in the same field. It is true, as Mr. Bell suggests, that some of the measurements, more especially of input admittance, can be performed with simple apparatus such as tuned circuits, but the effects of drift in the frequency of the oscillator supplying the power can only be conveniently and wholly eliminated by using bridge equipment. For the separation of ΔC_{ag}, resort must be made to a bridge provided with a Wagner earthing system.

Mr. Benham's contribution deals in particular with the quantity ΔC_{ag}. The theory which he presents takes account of transit-time effects. In view of the agreement shown in Fig. 3 between the results of measurement at 100 kc. and at 1 000 kc., it is doubtful whether transit-time effects are very significant at these frequencies. The expression which he derives for $(\Delta C_{ga} - \delta C_{ga})$, however, is very interesting and may prove useful at higher frequencies.

With regard to the circuit shown in Fig. 2, any direct admittance between anode and filament should be effectively compensated by the Wagner earthing arrangement.

As regards the first point made by Mr. Benham, it should be borne in mind that the measurements were not pursued into the region of grid current, as the conductance involved was liable to affect the interpretation to be placed on changes in C_{fg}. The downward trend at the upper reaches of the curves for the lower anode voltages in Figs. 3 and 5 is probably due to the incidence of grid current.

* See R. F. J. JARVIS: Thesis approved for the degree of Doctor of Philosophy in the University of London, 1933, p. 65; also P. H. J. A. KLEYNEN: *Philips Technical Review*, 1937, vol. 2, p. 338 (particularly Fig. 8, facing p. 345).

UNVEILING OF MEMORIAL TABLET TO ALEXANDER GRAHAM BELL

A memorial tablet to the late Alexander Graham Bell, which has been erected by The Institution of Electrical Engineers at the left-hand side of the doorway to 16 South Charlotte Street, Edinburgh, was unveiled on the 24th November, 1937, by Sir George Lee, President of The Institution. The wording on the tablet is:

"ALEXANDER GRAHAM BELL,
Inventor of the Telephone,
Born here 3rd March 1847."

An extract from the register of births and baptisms for the parish of Edinburgh, relating to the birthplace of Alexander Graham Bell, is reproduced on page 224.

The proceedings at the unveiling, which were broadcast by the B.B.C. in the Regional programme, were presided over by Mr. E. Seddon, City Electrical Engineer, Edinburgh.

Sir George Lee (who read a message from 22 members of the Bell family living in the United States) said :—

"We are met here this morning to do honour to one of the sons of Edinburgh, Alexander Graham Bell, whose work and inventions have been of such lasting benefit to every country of the world. His most famous invention, the telephone, enables us in these days to maintain conversation with our intimate friends and relations all over the globe; and broadcasting, as well, is dependent upon the telephone as its primary means of transmission.

"Bell's work, however, covered many phases of humanitarian and scientific activities. His work, as a teacher to the deaf and dumb and in the development of correct methods of teaching, was one of the most consuming passions of his life, and many of these unfortunate people, still alive, bless the name of Bell for enabling them to speak. His interest in the work of voice production was the direct stimulus to his efforts to invent the telephone.

"Alexander Graham Bell was born in this house, 16 South Charlotte Street, Edinburgh, on the 3rd March, 1847. His grandfather, Alexander Bell, was a recognized authority on the teaching of speech, and his father, Melville Bell, was even more famous in the subject of speech production and was the inventor of a system, known as 'visible speech,' in which the symbols represented the various positions of the vocal organs. The reader had merely to arrange his lips, tongue, etc., in the positions indicated to produce the sound desired. The spoken language of the Chinese was the first foreign language to be translated into 'visible speech.'

"After the birth of Alexander Graham Bell the family moved to 13 Hope Street, and finally to 13 South Charlotte Street, where Bell lived as a boy. This was supplemented by a cottage at Trinity, then in the country, which provided an out-of-doors playground.

"At 10 years of age he went to a private school in Edinburgh, and later he attended Dr. Donaldson's class at the Royal High School. By his own account in later years he was lazy, but he could not have been very idle, seeing that he duly graduated at 14 years of age.

"It is, of course, somewhat difficult at this late date to verify all the movements of the Bell family in the various houses in Edinburgh, and I have therefore taken as my authority the very interesting work by his secretary, Catherine Mackenzie, who had access to all the family records which were available.

"On leaving school, he spent a year in London with his grandfather, who stimulated him effectively in reading and learning. His grandfather, he used to say, 'made him ashamed of his ignorance.' Here he became familiar with his grandfather's voice-teaching methods and practised elocution.

"Returning to Scotland he obtained a post at Mr. Skinner's school at Elgin, where he taught music and elocution. He made researches into the resonance of the mouth cavities and experimented with tuning-forks and electromagnets.

"In the meantime, his father, Melville Bell, was achieving fame in various directions and had become Professor of Elocution at the University of London. His system of 'visible speech' attracted attention everywhere, and his methods of teaching elocution became the vogue of the time.

"At the height of this professional success, tragedy fell in the midst of the family. Two of Graham's brothers died of pulmonary disease and the only remaining son, Graham, showed signs of developing the same trouble. The father, without hesitation, sacrificed his professional career, and also the fame for which he had worked so tirelessly, and at 51 years of age he emigrated with his wife and son to a farm in Canada in order to enable the young man to recover his health in the open spaces of that country. They settled down at Brantford, Ontario, where the son very quickly recovered his health.

"The demands on the services of both father and son from New England for lectures and teaching brought Graham finally to Boston, where he taught at the School for the Deaf and also lectured on voice production.

"Here he commenced his experiments to produce electric speech, and in June, 1875, he first succeeded in transmitting intelligible speech over a wire.

"The story of the telephone has been told in detail elsewhere. It is a story of long suffering, work, and effort, by Bell, in which his genius finally attained success. He set out to invent the telephone: it did not come by accident. There was no previous theory to guide him, and he was working all the time on the frontiers of knowledge. His indomitable efforts and clear thinking finally solved all the difficulties.

"Honours were late in coming to Bell, but when they did, from scientific institutions and universities in all the principal countries, they were showered upon him. In 1920, Bell revisited Scotland to see some of the old haunts of his youth, and in the autumn of that year the

Lord Provost of Edinburgh conferred the Freedom of the City upon him. Bell was very proud of this honour, and on the return journey to America, on landing at St. John,

16 South Charlotte Street, which has been erected by The Institution of Electrical Engineers to commemorate the birth of a famous son of Scotland in this house. May

EXTRACT OF AN ENTRY

IN A REGISTER KEPT AT THE GENERAL REGISTRY OFFICE, EDINBURGH.

In terms of 25° & 24° Vict. cap. 85, sect. 6, and 10 Edw. VII. & 1 Geo. V., cap. 32, sect. 1.

Bell

Edinburgh, 12th September 1847

Alexander Melville Bell, Professor of Elocution and Eliza Grace Symonds, his Spouse, had

A lawful Son born at No. 16 South Charlotte Street, Saint George Parish   on the Third day of March Eighteen hundred and forty-seven Named Alexander ... effect the said Alexander Melville Bell made a Solemn declaration before one of Her Majesty's Justices of the Peace.

EXTRACTED from the REGISTER of BIRTHS and BAPTISMS for

the Parish of Edinburgh

in the County of Edinburgh

GIVEN at the GENERAL REGISTRY OFFICE, NEW REGISTER HOUSE,

EDINBURGH, under the Seal of the said Office, the 17th

day of December 1936.

In terms of the 6th section of the Act 23 & 24 Vict. c. 85, and the 57th section of the Act 17 & 18 Vict. c. 80, every person is entitled to search the Parochial Registers of Births or Baptisms, Deaths or Burials, and Marriages or Proclamations of Banns, and any relative Inventories or Indexes, in the custody of the Registrar-General on payment of a fee of Twenty Shillings for a General Search, and One Shilling for a Particular Search, and to have an Extract of any Entry in the said Registers for the further sum of Two Shillings, exclusive of Stamp Duty (54 & 55 Vict. c. 39, sect. 64) of One Penny.

By the Act of 10 Edw. VII. & 1 Geo. V., c. 32, sect. I, it is enacted " that the Registrar-General shall cause to be made a Seal of the " said General Registry Office, and the Registrar-General shall cause to be sealed or stamped therewith all Extracts of Entries given in the " said Office; and all Extracts of Entries purporting to be sealed or stamped with the Seal of the said General Registry Office shall be " deemed to be duly authenticated by the Registrar-General."

Any person who falsifies any of the particulars on this Extract and makes use of the same as true, knowing it to be false, is liable to prosecution.

Bell, who was carrying the silver casket presented to him by the Lord Provost, was asked by the Customs Officer, ' What have you there, sir ? ', and replied ' The freedom of my native city, sir.'

" I now have the honour of unveiling this tablet on

it serve to remind us that genius is a very precious gift to humanity, and that such genius as Bell's is one of the landmarks in the progress of civilization."

After the unveiling a luncheon was given in the

Charlotte Rooms by Lieut.-Col. F. N. Westbury (*Scottish Regional Director to the Post Office*).

At the luncheon **Prof. G. W. O. Howe** said :—

" We have to-day conferred a threefold honour: we have honoured a man, a city, and science. We have honoured a man, a man who in his lifetime received many great honours but who, I feel sure, could he have known what we have done to-day in the city of his birth, would have counted it the greatest honour ever conferred upon him. We have honoured the City of Edinburgh by placing on record that it numbers among its sons the man whose name will for ever be associated with the invention of the telephone—a man whose name is written large across the American Continent, the land of his adoption, and borne by one of the greatest, if not the greatest, scientific research laboratories of the world—a man who has been made one of that band of immortals—Volta, Ampère, Watt, Ohm, Faraday, Henry, Joule, Maxwell—whose names are for ever enshrined in the nomenclature of science.

" As Dr. Ferguson said in a lecture before the Society of Arts in this city on the 14th January, 1878, ' While we do not grudge America the credit of the telephone, we recognize with pride that the inventor is a native of this city, and that his respected father was an active member of this Society.'

" And we have honoured science by our recognition of the greatness of the man and of his achievement. In this city are many monuments to those who have distinguished themselves in art and letters, in politics and war. We have to-day unveiled a monument to one who was distinguished in a branch of human activity in no way inferior to any of these—in applied science, in the conquest of the secrets and forces of nature and their application and development in the service of mankind.

" The tablet which has been unveiled to-day states that Alexander Graham Bell was the inventor of the telephone, and it may be asked whether this ascription is justified. Have not other men been given the credit for the invention? What justification have we for giving the credit to this son of Edinburgh? It was because these questions had been asked that I became more intimately associated with the memorial, and I feel it to be my duty to answer them. When the proposal came before The Institution of Electrical Engineers, the Secretary, knowing that divergent opinions had been expressed on the subject, showed a proper caution and asked me if I would look into the matter. He sent me a large number of books dealing with the early history of the telephone. I need only refer to one of these—a book written many years ago by the late Professor Silvanus Thompson and entitled ' Philipp Reis, the Inventor of the Telephone.' This book I read and re-read, and, strange to say, it removed any doubts which I may have had as to the justification for regarding Alexander Graham Bell as the inventor of the telephone. Philipp Reis was a German teacher living in the country near Frankfort-on-Main, who devoted years of patient research to the problem of telephony; he made several transmitters and receivers, and gave a demonstration before a Science Congress in 1864, but then apparently gave it up, for no further progress appears to have been made; the matter was allowed to drop, and Reis died in

1874. Professor Thompson visited his home and interviewed his widow and others who had known Reis and taken part in his experiments, but although he did everything possible to make out a case for Reis, I have no hesitation in saying that there is no reliable evidence that Reis ever succeeded in transmitting a single sentence of intelligible speech. His transmitter was a make-and-break apparatus, capable of transmitting tones and therefore tunes, and very simple vocal sounds. There is no doubt whatever that his object was to transmit speech. Twenty years after the demonstration, Professor Quincke said that he distinctly remembered having heard the words of the German poem ' Ach! du lieber Augustin, Alles ist hin!' but seeing that this is a well-known German song, the words would come automatically to the mind of any German on hearing the tune merely hummed. The strongest proof that the Reis telephone was incapable of transmitting intelligible speech was provided by the American experts who, in their efforts to prove that Reis anticipated Bell, obtained some Reis telephones from Germany and tried their utmost to make them work. In the controlled tests, out of a thousand words the listeners recognized 15, and 8 of these were wrong!

" Nor was Bell's invention in any way a development from Reis. The underlying principles were entirely different. Reis describes his apparatus very clearly, and in the light of our present knowledge—or even of the knowledge of the nature of speech which Bell possessed in 1875—it is obvious that such a make-and-break device could not possibly transmit intelligible speech. Bell's great conception was to transmit an undulating current varying in intensity in accordance with the complex movements of the air particles which constitute the sound wave. He was experimenting with multiple-tone telegraphy when a fortunate accident gave him a clue to the production of such a ' sound-shaped current.' What to many would have been merely an annoying occurrence was to Bell a blaze of light, and from that moment he had but one object in life. As he wrote to his parents in Canada ' Such a chimerical idea as telegraphing *vocal sounds* would indeed to *most minds* seem scarcely feasible enough to spend time working over. I believe, however, that it is feasible, and that I have got the cue to the solution of the problem.'

" Much confusion was caused by the indiscriminate use of the words ' telegraphy ' and ' telephony.' The latter name had been applied since about 1841 to purely mechanical arrangements for transmitting sounds through wooden rods, and when applied to electrical methods referred merely to the transmission of sound and not necessarily to speech. For this reason Bell's invention was sometimes referred to as an ' articulate telephone,' but now this distinction is no longer necessary and when we say that Bell invented the telephone it is understood that we refer to an apparatus by means of which intelligible speech is transmitted by electrical methods. The great value of Bell's invention can be judged from the violence of the attacks made upon it, and its soundness from the failure of all the attacks. It was very fortunate that Bell was persuaded at the last moment to exhibit his telephone in its still imperfect form at the Centennial Exhibition in Philadelphia in 1876, and that one of the judges was Sir William Thomson, afterwards Lord

Kelvin. Kelvin's opinion helps us to form a correct estimate of the invention in the light of the most advanced knowledge of the time. Professor Hunt writing to Bell on the same evening says ' Sir William Thomson speaks with much enthusiasm of your achievement. What yesterday he would have declared impossible he has to-day seen realized, and he declares it the most wonderful thing he has seen in America. Your undulating current he declares a great and happy conception.' In his address to the British Association on his return he said —and it illustrates the mixed use of the words ' telephony ' and ' telegraphy '—' I saw and heard Elisha Gray's splendidly worked-out *electric telephone* actually sounding four messages simultaneously *on the Morse Code* . . . and I saw Edison's automatic telegraph delivering 1 015 words in 57 seconds; this done by the long-neglected electrochemical method of Bain. . . In the Canadian department I heard 'To be or not to be. . . there's the rub ' through an electric telegraph wire; but, scorning monosyllables, the electric articulation rose to higher flights, and gave me passages taken at random from the New York newspapers. . . All this my own ears heard. . . This, the greatest by far of all the marvels of the *electric telegraph*, is due to a young countryman of our own, Mr. Graham Bell. . . Who can but admire the hardihood of invention which devised such very slight means to realize the mathematical conception that, if electricity is to convey all the delicacies of quality which distinguish articulate speech, the strength of the current must vary continuously and as nearly as may be in simple proportion to the velocity of a particle of air engaged in constituting the sound?'

" I feel that Kelvin is with us here to-day in spirit, doing honour to his fellow countryman.

" There is a popular fallacy that I wish to correct and that is that Bell only invented the electromagnet telephone. He fully realized the possibility of producing the undulations in the current by means of a variable resistance, and he experimented with a transmitter in which a wire attached to the diaphragm dipped into a cup containing weak acid. His original patent contained a variable-resistance clause. Subsequent inventors devised improved methods of carrying out this conception.

" It has been suggested that Bell was not a scientist. In the paper previously referred to, read in 1878 before the Royal Scottish Society of Arts, Dr. Ferguson said ' Professor Graham Bell was in the first instance professionally non-scientific. One would almost fancy, if he had been specially scientific, educated caution would have warned him off from such an apparently unlikely and hopeless problem. To make the feeble voice of man speak to the uttermost ends of the earth as it no doubt yet will do, seemed beforehand a mere visionary project.' Now I want to dispel this myth. He had not been trained as a physicist or telegraph engineer, but he was a specialist in the science of speech and acoustics, and his dream of transmitting speech electrically had grown out of his expert knowledge of the voice, and the physical mechanism of speech. He was not, as Dr. Ferguson said, a Professor of English Literature but of Vocal Physiology in the Boston School of Oratory. The following quotations will, I think, show that he was an experi-

enced experimental scientist and that, however deficient his electrical knowledge may have been in the initial stages, he had assimilated a considerable knowledge during the working out of his invention. In connection with teaching the deaf and dumb, he says ' For some time I carried on experiments with the manometric capsule of Koenig and with the phonautograph of Léon Scott. The scientific apparatus in the Institute of Technology in Boston was freely placed at my disposal for these experiments.' In a paper which he read before the Society of Telegraph Engineers in London on the 31st October, 1877, he said ' I saw no reason why the depression of a number of keys at the tuning-fork end of the circuit should not be followed by the audible production of a full chord from the piano in the distant city ' . . . ' I did not rest until I had obtained possession of a copy of Helmholtz's great work ' (Theory of Tone) . . . ' The interest which I felt in electricity led me to study the various systems of telegraphy in use in this country and in America.' More than a year before this, viz. on the 2nd July, 1876, Bell wrote the following letter:—

" ' In preparing for transmitting sounds to Philadelphia from here, I made such a startling discovery that I have been unable to do anything else since but experiment. In order to attempt the transmission of speech to Philadelphia, it was necessary to have a telephone constructed, the magnet of which should have a resistance equivalent to a considerable portion of the total resistance of the telegraph line between here and Philadelphia. The resistance of the line is over 5 000 ohms. Now I have had two magnets made the coils of which offer a resistance of 3 250 ohms both together. It would require a battery of many cells in order to operate a Morse sounder through such a resistance. It is as great a resistance as 325 miles of well-insulated telegraph wire. My discovery was that I could work my apparatus with *one cell of a battery* through this resistance. I am sure by substituting a *permanent magnet* for the pole of the electromagnet I could work it *without a battery at all*.

" ' With love and best wishes, Yours sincerely,

A. Graham Bell.'

" Here we see the birth of the permanent-magnet receiver, and we also see that Bell was fully alive to the necessity of matching the resistance of the terminal apparatus to that of the line. It is abundantly clear that his refusal to be ' warned off the apparently unlikely and hopeless problem ' was not due to any lack of scientific training or ignorance of electricity but to the ' enthusiasm and burning belief that was part of his genius and which animated all his work.'

" The secret of his great achievement is to be found in his character, and I am grateful for this opportunity of paying tribute to the memory of Alexander Graham Bell who was born here in Auld Reekie on the 3rd March, 1847, and passed away, as was most fitting, in Nova Scotia on the 2nd August, 1922."

Mr. F. Gill (*Past-President*), Dr. L. F. Morehouse (representing the American Telegraph and Telephone Co.), Mr. J. E. Kingsbury, Mr. F. G. C. Baldwin, Mr. J. J. McKichan, and Bailie E. Walker, J.P., also spoke.

INSTITUTION NOTES

HONORARY MEMBER

At the Ordinary Meeting of The Institution held on the 20th January, 1938, the President announced that the Council had elected Mr. Frank Gill, O.B.E., Past-President, to be an Honorary Member of The Institution.

FARADAY MEDAL

At the same meeting the President also announced that the Council had made the sixteenth award of the Faraday Medal to Sir John Snell, G.B.E., Past-President.

SUMMER MEETING, 1938

The Summer Meeting of The Institution will be held in Birmingham and district from Monday, 4th, to Friday, 8th July, at the invitation of the Chairman and Committee of the South Midland Centre.

Full particulars will be circulated at an early date.

DEVON AND CORNWALL SUB-CENTRE

The Council have adopted a recommendation of the Western Centre, that a petition from a number of members resident in Devon and Cornwall for the formation of a Sub-Centre in that area be approved.

An Interim Committee has been nominated by the Western Centre Committee to carry on the business of the Sub-Centre until the end of the present session, and the following interim officers have been appointed: *Chairman:* H. Midgley, M.Sc.; *Hon. Secretary:* W. A. Gallon, B.Sc.; *Hon. Treasurer:* S. G. Monk, M.Sc.(Eng.), B.Sc.

The first meeting of the Sub-Centre was held at Plymouth on the 28th January, when the Chairman delivered an informal address. Further meetings have been arranged for the remainder of the session as follows:—

Monday, 28th February, at Exeter; Friday, 25th March, at Plymouth; Monday, 25th April, at Torquay.

JOINT MEETING OF KINDRED SOCIETIES, 1st MARCH, 1938

The Council have accepted an invitation from The Institution of Automobile Engineers for the I.E.E. to participate in a Joint Meeting of Kindred Societies to be held on Tuesday, 1st March, 1938, when the following papers on the subject of " Essential Road Conditions Covering the Safety of Modern Traffic " will be read and discussed:—

" Road Planning," by Dr. T. Adams.

" Road Construction," by Mr. C. Howard Humphreys.

" Road Illumination," by Messrs. L. J. Davies and G. S. Lucas.

The meeting will be held in the Great Hall of The Institution of Civil Engineers, Great George Street, Westminster, S.W.1, at 7 p.m. (Light refreshments 8.15 p.m. to 8.45 p.m.)

A limited supply of advance copies of the paper will be available and can be obtained free of charge before the date of the meeting, on application to the Secretary, I.E.E. Copies of the paper will also be available at the Hall on the night, but only on payment of 1s. 6d. per copy.

JOINT MEETING WITH THE INSTITUTION OF CIVIL ENGINEERS

The Council have accepted an invitation from The Institution of Civil Engineers to hold a Joint Meeting on Tuesday, 22nd March, 1938, when two papers on the Fulham Power Station will be read: one, by Mr. J. F. Hay, dealing with the civil engineering works, and the other, by Messrs. W. E. Parker and H. Clark, dealing with the electro-mechanical aspect.

The meeting will be held in the Great Hall of The Institution of Civil Engineers, Great George Street, Westminster, S.W.1, at 6 p.m. (Light refreshments 5.30 p.m.)

A supply of advance copies of the papers will be available about 10 days before the meeting, and any member of the I.E.E. desiring to receive a copy should apply to the Secretary, The Institution of Electrical Engineers, Savoy Place, London, W.C.2.

DISCUSSIONS AT MEETINGS

The Council desire to remind the members that contributions to the discussions at meetings should not be read from manuscript, the view being held that the presentation of remarks in this manner is contrary to the true spirit of a " discussion," and that contributions in manuscript should, more appropriately, be sent to the Secretary for publication in the *Journal* as " communicated remarks."

NATIONAL CERTIFICATES AND DIPLOMAS IN ELECTRICAL ENGINEERING

The following are the results of the examinations in connection with the above for the year 1937:—

England and Wales

	Pass	Fail
Ordinary Certificate	816	640
Higher Certificate	407	233
Higher Certificate endorsed	62	19
Ordinary Diploma	27	10
Higher Diploma	16	4
	1 328	906

Scotland

	Pass	Fail
Ordinary Certificate	38	8
Higher Certificate	18	1
Higher Diploma	7	—
	63	9

OVERSEAS MEMBERS AND THE INSTITUTION

During the period 1st October, 1937, to 31st January, 1938, the following members from overseas called at The Institution and signed the "Attendance Register of Overseas Members ":—

Berenbaum, A., B.Eng. (*Haifa*).
Berman, M. E., M.Eng. (*Jerusalem*).
Blofeld, T. G. (*Tarkwa, Gold Coast Colony*).
Browne, B. F. (*Santos, Brazil*).
Da Costa, F. A. V. (*Praia da Rocha, Portugal*).
Desai, C. S. (*Kericho, Kenya*).
Earle, R. E. (*Singapore*).
Field, H. J. (*Queensland*).
Gee, W. C. (*Kuala Lumpur*).
Glasse, A. O. (*Auckland, New Zealand*).
Hahn, O. H., Ph.D., M.Sc. (*Johannesburg*).
Harmer, L. B. (*Shanghai*).
Jones, C. H. (*Colombo*).
Kendall, Major R. (*Melbourne*).
Lawson, D. G. M., B.Sc.(Eng.) (*Zomba, Nyasaland*).
MacDiarmid, S. C., B.E. (*Hamilton, New Zealand*).
Noble, H. J. G. (*Shanghai*).
Patel, B. J. (*Bombay*).
Patrick, W. McC. (*Shanghai*).
Perrow, E. V. (*Johannesburg*).
Radford, J. S. (*Perth, Australia*).
Wainscott, P. D. (*Bombay*).
Walden, H. de Faye (*Trinidad*).
Winson, V. H., B.Sc.(Eng.) (*Kuala Lumpur*).

GRADUATESHIP EXAMINATION RESULTS: NOVEMBER, 1937

Passed*

Bailey, Albert Thomas.
Bateson, Alan.
Binny, John Graham.
Brocklesby, Frederick Norton.
Bullen, Harold Howe.
Campbell, James.
Carrothers, John Kelly.
Dasgupta, Amalkumar.
Dobson, Arnold Tidswell.
Eckett, Sidney Wallace.
England, Ralph.
Fawssett, Phyllis Armorel M. (Miss).
Florida, Charles David.
Franklin, Alfred Leslie.
Gates, Norman Percival.
Hall, Robert Henry.
Hammersley, Harold Ewart B.
Higgins, William Godfrey G.
Hilyer, Frederick Gordon.
Hussain, Syed Naseer.
Jeffery, Derek William.
Jenkins, Llewellyn Evans.
Krishnan, Rishiyur Subrahmanyam.
Litchfield, Wilfred.
Lowne, Hugh Reginald B.
MacGregor, James Gillespie.
McLoughland, Thomas.
Marshall, John Carlile.
Mendis, Terence William.
Parr, Asa.
Parry, Reginald Charles.
Perkins, Henry Whitworth.
Reynolds, Herbert.
Smillie, Ronald.
Squires, Mordecai.
Terrell, Basil Joseph.
Tucker, Maurice Albert.
Williams, Arthur Parry.

Passed Part I only

Ballard, Walter George.
Batcock, Bernard John.
Dolman, Frank Kenneth.
Dukes, Frederick Ernest.
Gibson, Albert James.
Hollingworth, Stephen Ian.
Housego, Stanley Newman.
Jameson, John Francis.
Joice, William Arnold.
Knowles, John.

* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Passed Part I only—*continued*.

Little, Alfred William G.
McBain, John.
Meher-Homji, Jal Ardeshir.
Muirhead, David Pearson.
Phillips, Alban William.
Price, John Elwyn.
Shipway, Ernest Lionel M.
Smith, Alexander Sharp.
Tandy, Thomas Henry.
Taylor-Thomas, Richard.
Wilcock, Arthur Camplin.
Woods, John Victor.
Young, Andrew Anderson.

Passed Part II only

Cottrell, Seymour.
Grimes, Wilfred Wallace.
Quincey, Stanley Arthur.
Sear, Norman Charles A.
Weaire, Reginald Frederick.
White, Harry William N.

Further results, relating to candidates who sat for the Examination abroad, will be published later.

ELECTIONS AND TRANSFERS

At the Ordinary Meeting of The Institution held on the 20th January, 1938, the following elections and transfers were effected:—

Elections

Member

Hawthorne, William, B.A., B.E.

Associate Members

Baker, Cecil Graham.
Baker, Henry Edmeades, B.A.
Banbury, Leonard Glanville.
Boocock, Ralph Oron, B.Sc.(Eng.).
Brazier, Kenric Stuart, B.Sc.
Bryant, Reginald.
Chantrill, Guy, B.Sc.(Eng.).
Court, Philip Arnold, B.Sc.(Eng.).
Crofts, John White, B.A.
Davies, Bernard Rees, B.Sc.(Eng.).
Dryland, Leslie Watson J.
Dummelow, John, M.A.
Fabian, Henry Charles.
Goodman, Howard Roi.
Grainger, Gordon.
Greenwood, George Charles.
Haliburton, Frederick Charles.
Hamilton, Donald Fraser.
Hamson, Paul, B.Sc.Tech.
Harding, Horace Ralph.
Harley, Harold James, B.Sc.(Eng.).
Hawkes, Harry Donald.
Hough, Francis Alexander, M.Sc.(Eng.).
Huggard, Joseph Pritchard, B.Sc.
Johnstone-Hall, Raymond Thomas R., B.Sc.(Eng.).
Josephs, Henry John.
Kell, Robert, B.Sc.(Eng.).
Kernick, Richard Seymour.
Knapman, Donald Edward, B.Sc.(Eng.).
Leake, Francis William.
McDonald, Andrew, B.A.
McHattie, Joseph, B.Sc.
MacLarty, Basil Neil, O.B.E.
Marstrand, Otto Jens, Major, R.E., M.C., B.Sc.
Mason, Denis Clifford, B.Sc.
Mason, Martin Summerfield.
Nemet, Anthony, Dipl. Ing., Dr.Ing.
Olver, George Corden, B.Sc.(Eng.).
Pearce, Arnold Ponteus.
Pulley, Oliver Owen, B.E., Ph.D.
Reid, Charles.
Rowbotham, Clifford.
Salt, Roy Stewart, B.Sc.(Eng.).
Sleenan, Hector.
Smith, Leslie Morgan.
Southwick, Alfred.
Spears, George.
Stone, Alfred Ernest.
Vickers, Herbert, Ph.D., M.Eng.
Whitaker, Herbert, B.Sc.
Wilkinson, George Barlow, M.A.

Associates

Axten, Bernard John.
Belcher, Horace John.
Bird, Maurice.
Bose, Basu.
Brown, William John.
Caswell, Arthur Edward, B.Sc.
Cripps, Charles Fruin.
Dunster, Basil Newport.
Duthie, Donald.
Eddershaw, Bernard.
Gifford, Charles Laurence.
Glendinning, Acheson Harden, B.Sc.
Hemmer, Albert Alphonse E., B.Sc.

Higson, John.
James, Gilbert Oliver.
Jones, John Henry.
Newth, John.
Pitt, Frank Ernest.
Roughton, Ernest Alfred.
Semmens, Ernest William.
Shuttleworth, Herbert.
Skinner, Leslie Douglas.
Smyth, Charles Frederick.
Springate, Frank.
Thompson, Augustus Henry.
Turner, Frederick.
Wishart, John.

Graduates

Atkinson, Geoffrey, B.Sc.
Bakes, Wilfred.
Banerjee, Ranjit Kumar.
Bao, Sing Dee, B.Sc.
Bates, Donald Laurence, B.A.
Batty, Kenneth Thomas.
Behrens, Teodoro Adolfo, B.Sc.
Broughton, Eric.
Brownless, Sidney Frank, B.Sc.
Calverley, Henry Bolton, B.Sc.(Eng.).
Calvert, Angus Cameron.
Carr, Clifford.
Chilvers, William George H.
Collie, John, B.Sc.(Eng.).
Collier, Percival Gerard.
Conford, Anthony George, B.Sc.(Eng.).
Cooper, Edmund Curtis.
Cox, Stanley Austin, B.Sc. (Eng.).
Crosby, Philip Norman.
Crosfield, John Fothergill, B.A.
Davis, Ronald Bernard, B.Sc.(Eng.).
Deacon, John Alfred.
Deason, John Noel.
Dewan, Hargobind, B.Sc. (Eng.).
Dixon, William, B.Sc. (Eng.).
Duff, Duncan.
Duncan, Ronald Andrew, B.Sc.
Edmunds, Archibald James.
Ellis, Roy, B.Eng.
Evans, Gwilym Owen, B.Sc.
Fahey, Basil, B.Sc.

Fairweather, Donald.
Fernbach, Hans Rainer.
Fryer, Patrick William F., B.Sc.(Eng.).
Furneaux, Edwin George.
Gabrielides, Gabriel Alexander, B.Sc.
Gibson, Norbert James.
Glanister, Charles William.
Greatrex, Ferdinand Basil, B.A.
Green, Robert Alan.
Gregory, Cyril Ambrose.
Haigh, Frederick Roebuck, B.Sc.
Hammersley, Colin.
Harrison, John Dennis.
Harverson, Henry Wilton.
Hathaway, Richard.
Heyes, Oswald, B.Sc.
Hickox, William Frederick.
Hinde, Douglas Wylie, B.Sc.
Hodgson, West.
Holdsworth, Bernard.
Hume, John McIntosh.
Illingworth, Brian Garfield, B.Sc.(Eng.).
Iyer, Krishnaswamy Parameswara, B.A.
Jacoby, George Arthur.
Jarvis, Edward Alfred K., B.Sc.(Eng.).
Jones, Richard, B.Eng.
Kapre, Purushottam Krishna, Ph.D.
Keir, Ronald John.
Kennedy, Alexander Milroy, B.A.
Khan, Mirza Shamsuddin.
Lapidge, Jack Stanley, B.E.
Lappe, Rudolf Eduard, B.Sc.(Eng.).

Lewis, Harold.
Locker, Leonard.
Lord, Arthur George, B.Eng.
Marriott, Harry, B.Eng.
Martin, Charles Hugh, B.Sc.
Mathur, Ram Narain, B.Sc.Tech.
Mehler, Maxwell John, B.Sc.
Menon, Karunakara Menon G., B.Sc.(Eng.).
Milner, Solly Max, B.Sc. (Eng.).
Mohsenin, Abdul Majid, B.Sc.
Moss, Hilary, B.Sc.(Eng.).
Murgatroyd, Colin.
Nettles, Richard Geoffrey, B.Sc.
Newbigging, Ian Balmford, Flight Lieut., R.A.F.
Nouri, Amir Houshang N., B.Sc.
O'Donnell, Terence Patrick.
Parkinson, Charles Eric, B.Eng.
Phillips, Henry Maurice B., B.Sc.(Eng.).
Phillips, Percy Ernest.
Plioushtch, Igor.
Preston, Derek George.

Rodrigo, Joseph Simon F., B.A., B.Eng.
Ronald, Thomas Towers.
Russell, George.
Simpson, Robert Taylor.
Snow, Claude Ivan, B.A., B.Sc.
Spooner, Jack Walter.
Subbarao, Josyula Venkata.
Tekant, Ahmet Naim.
Terry, Michael Treacher, M.A.
Thomson, Alistair Gosman, B.Sc.
Tucker, Harold Clayton, B.Sc.(Eng.).
Twist, Arthur Nicolas.
Walker, Ronald Wesley.
Ward, Ian Malcolm L., B.Sc.Tech.
Weighton, Donald, B.A.
Wells, John Trevor, B.Eng.
Whiley, Eric George.
White, Robert Williamson, B.Sc.
Wilkins, John Ambrose, B.E.
Wilkinson, Geoffrey Seymour.
Wilson, Harry.
Wood, Henry Stephen.
York, Stanley.

Students

Abbott, Norman Percy.
Abel-Harry, Clifford Barrington.
Abramis, Boris Dov.
Adams, John Bertram.
Adams, Norman Frank.
Agate, Jeffery Stanford.
Ahluwalia, Gurbakhsh Singh.
Ahluwalia, Ugra Sen.
Ahmad, Sarfraz.
Ahwai, Choy Eldon.
Alagaratnam, Candiah.
Alexander, John Finlay.
Alexander, N. Thomas, B.A.
Allan, John.
Allen, Alexander Miall.
Allen, Harry Goodger.
Allen, Ronald Charles J.
Amberton, Anthony Richard.
Annable, John Arthur.
Anstie, Robert Denis.
Anwyl, Edward.
Appa, Narayanaswamappa Dodda M.

Arnold, Leslie Albert.
Arora, Madan Lal.
Asher, Philip.
Asim, Syed Mohammad.
Atkinson, Frederick Booth.
Axworthy, Francis Roy.
Ayre, Maurice.
Aziz-ul-Hamid, Sahibzada Shiekh.
Babb, Alexander Hammond.
Badham, Ronald.
Baggott, Albert Jeffries.
Bahl, Dilbagh Rai.
Bakhru, Hasso J.
Baker, John William.
Baker, Ronald George.
Balasundaram, N.
Banerjee, Sadhanananda.
Banerji, Dhirendra Nath.
Banks, Peter Harry C.
Barker, Clarence Trevor.
Barker, Samuel Julian.
Barlow, Eric Roxburgh.
Barlow, Kenneth Frederick.

Students—continued.

Barnes, Cyril Charles.
Barsky, Gideon.
Basford, Aubrey Newton.
Bate, Leslie Arnold E.
Bates, Maharaj Krishan.
Bays, Charles Frank.
Beales, Frank William.
Beckett, John Douglas H.
Bending, Bernard Claude.
Bennett, Edward George.
Bennett, Frederick James.
Betteridge, Philip.
Bhagawat, Sadashiv Ramchandra, B.Sc.
Bharucha, Phiroze Darabshaw, B.A.
Bhatia, Manmohan Singh.
Bhatnagar, Brahm Bhushan.
Bhattacharya, Mohit Kumar.
Bhullar, Sohan Singh.
Bird, Gordon Alfred.
Bishop, James Brown.
Biswas, Amar.
Blackmore, James Henry.
Blanco, Angel Alberto.
Bogle, Richard Kennedy.
Boswell, Robert William M., M.Sc.
Booker, Douglas Wilfrid.
Brew, William Richard.
Brewitt-Taylor, Edward Gordon.
Broad, John Harold S.
Brockelsby, Harry.
Brook, Edric Raymond.
Brooks, George Roderick.
Bruce, Alan.
Bruce, Neil Pettigrew.
Buck, Percy Elliott.
Buckland, Walter George N.
Burgess, David Alexander.
Burton, Donald Ernest.
Busby, Robert Johnson.
Butcher, George Edgar.
Cannell, Cyril Everatt.
Carlton-Jones, Percy John.
Carroll, George Daniel.
Catto, Eric Herbert.
Chahuan, Pushpsinh Raisinghge.
Chandler, Robert Walter.
Chandra, Avadhesh.
Chandra, Harish.
Chandrasinghe, Don Paul.
Chatterji, Indra.
Chaturvedi, Govind Kashiprasad.
Chetwood, David Hugh.
Chiang, Ts-En.

Ching, Fredrick Douglas.
Clarke, John Henry.
Clifford, Henry Phillimore.
Cohen, Theodore David.
Choksey, Dorab Khursed.
Coker, Jaiyeola Olubode.
Coller, David Lonsdale.
Collette, Henry Herman, B.Sc.
Collins, Frank.
Collins, Frederick Henry.
Coueslant, Peter.
Cox, Donald Leslie.
Cox, William John.
Cowcher, Frederick George.
Cox, Ernest Francis.
Coyle, Arthur Douglas.
Craske, Maurince Allan.
Cross, Donald Ewart.
Crow, Denis Raymond.
Crowdy, Timothy David.
Curtis, James Eric.
Cutten, Esmond Latham.
Darnell, Herbert.
Das, Daleep Bruce.
Dasgupta, Amal Kumar.
Date, Gangadhar Laxman.
Davidson, George William.
Davies, Alun Madoc.
Davies, Arthur Linton.
Davies, Roy Travers.
Davis, David Thomas.
Davis, Jack.
De, Swayambhö Kumar.
Decottignies, Emmanuel Maurice E.
de Figueiredo, Bruno Filomeno.
Deshpande, Murlidhar Vinayak.
Deshpande, Prabhakar Raghunath.
Devereux, Geoffrey.
Dhar, Nemai Chand.
Dissanayake, Sirisena.
Diwan, Gyan Chand.
Dixie, Wilfred Douglas.
Dobbie, Arthur Kenneth.
Dookhie, Leslie Grant.
Downes, Edward.
Downey, Raymond Sinclair.
Dowsett, Jack Haig.
Druce, Kenneth.
Drybrough, David Allen S.
Duckitt, Harry, B.Sc.
Dunkley, William Gordon.
Eagle, John Scott.
Ebourne, Leonard Ernest.
Eccleston, Arthur.
Edgecombe, Gordon Henry.
Edwards, Paul Lionel J.

El Gammal, Abdalla Mahmoud.
El Rasheed, Mohammad Haleem.
Ensor, Gerald.
Evans, Peter Lowden.
Evans, Rinford.
Fearing, Alfred.
Ferguson, Harold Matthew.
Finlay, Michael.
Fisher, Cyril Kenneth.
Flashman, John Sydney.
Fletcher, Theodore Francis.
Forsyth, John Guy M.
Fox, Donald Ernest.
Francis, Edward Charles.
Fraser, James Anderson.
French, Arthur Simmons.
Fry, Anthony Ellerton.
Garwood, Arthur Frank.
Ghosh, Nikhil Krishna.
Gilchrist, John Anthony.
Gillott, Norman.
Goffe, Fredrick William F.
Goldman, Henry.
Goldschmidt, Kurt.
Goodman, Arthur Frederick.
Goodwin, John Lewis.
Gordon, Donal Matheson.
Gotety, Venkata Sreeramamurthy.
Gower, Denys King.
Gray, Frank Carter.
Greenhalgh, Kenneth Drew.
Greenwood, Leonard.
Greetham, Robert Frederick.
Gregory, Albert Edward.
Gregory, Ronald Hubert.
Guneratne, Nahallage Don W.
Halewood, William.
Hall, Graham George.
Hamp, James Edwin.
Harding, Kenneth Herman.
Harris, James.
Harrison, Donald.
Harrower, Thomas Murray.
Harskin, Mark.
Hart, George John S.
Hate, Prabhakar Dwarkanath.
Hattikudur, Dinkar Umanath.
Haywood, James Joseph H.
Heptinstall, Dennis Leonard.
Herbert, Raymond Mawson.

Hewlett, Stanley James.
Hill, Geoffrey George.
Hill, John Wreghitt.
Hillis, John Theodore.
Hodgson, Arthur Matthew.
Hoe, Gerald Francis.
Holbrook, George William.
Hope, Kenneth Herbert.
Hopkinson, Arthur.
Houlton, Edgar Moxon.
Housden, Gordon Arthur J.
Howard, John Purvis.
Howell, Cecil Moreton.
Hudson, John William P.
Hunt, Ronald Edward.
Hunt, Thomas Peter.
Hunt, Thomas William.
Hurford, Denis George.
Husein, Amir Ebrahim.
Hussain, Syed Naseer.
Hutton, Herbert Arthur.
Iago, John Martindale.
Ivanoff, Serge.
James, John Harold.
Jangalwala, Dara Dinshawji.
Jippes, Douwe Arie.
Johnson, Frank Louis.
Johnson, John.
Jones, Arthur Brynford.
Jones, Arthur Howel.
Jones, David Gower.
Jones, George.
Jones, Sidney Charles.
Jordan, Eric William T.
Joshi, Dattaraya Atmaram.
Joshi, Devki Nandan.
Jubb, Edward Hotham.
Karamelli, Alroy Harry.
Kay, Sydney Pitfield, B.Sc.
Keen, Herbert Charles C.
Kenyon, Roland Taylor.
Ketteridge, Maynard Harrison.
Khalil, Abdul.
Khasnis, Vasant Vinayakrao.
Krishnamurthi, Vaidyanath.
Krishnan, Rishiyur Subrahmanyam.
Kirk, James Mitchell.
Knight, Edward Frederick.
Knight, Stanley Frederick.
Kulkarni, Murlidhar Martand.
Kydd, James Mackay B.
Laight, Arthur Henry.
Lal, Manjit.
Lang, Robert Montgomery.
Laws, Cecil Alfred.
Lee, Harry.

Students—continued.

Lester, Frank Duckworth.
Lever, Herbert.
Lewin, Valentine Arthur.
Lewis, Arthur James.
Line, Reginald Charles.
Lockett, Reginald St. John.
Luckens, Fielden Spencer D.
Lund, James Arthur.
Lynch, George Daniel.
McCusker, Joseph Bernard.
McIvor, John William.
McKenna, James Threlfall.
McNair, John Ferguson.
McNeil, Peter Donald.
Malhotra, Krishan Kumar.
Manton, John Charles.
Marks, Albert Edward.
Marsh, Peter John.
Marshall, Douglas, B.Sc. (Eng.).
Marshall, Harry William S.
Martin, Robert Allen.
Maxwell, Peter Gordon.
Medhurst, Leonard John.
Medlock, Edwin Roy.
Meeson, Edwin Laurence, B.Sc.(Eng.).
Mehra, Raghbir Nath.
Mehta, Dinshaw Hirjibhoy.
Mehta, Praful Suryashanker.
Millard, Charles Arthur.
Minns, Richard Howard.
Minus, Eric Leslie.
Mirchandani, Metharam A.
Mitchell, Philip Henry G.
Mitchell, Sidney Charles.
Moir, Kenneth.
Moore, Thomas Edward R.
Morley, Stanley John.
Morrott, George Walter.
Morss, Alexander William.
Mort, Richard Frederick C.
Mortimer, Kenneth.
Moss, Eric.
Mukhless, Ghulam Hussain.
Mundkur, Balakrishnarao Sanjivrao.
Murad, Yusufali Haji M.
Mylvahanam, Kanapathy Pillay.
Nalder, Eric Martin.
Nambiar, Vasudevan.
Narasingham, C. R.
Narayanaiyer, P. I.
Narayanan, V.
Nath, Prem.
Natu, Ramachandra Vishwnath.

Newman, Durnford Frederick W.
Newman, George William.
Nichols, Thomas.
Nicholson, John William H.
Nixon, Cecil Walter.
Noxon, John Roger.
Ochani, Utamsing Gurmukhsing.
Oliver, Robert.
Ong, Kean Hor.
Ord, William Frederick.
Owen, George Rhonwy.
Palekar, Dattatraya Wasudeo, M.Sc.
Palmer, Richard Alan.
Panshikar, Chandrashekhar Vishnu.
Parkin, Peter Hubert.
Parry, Frank.
Parsons, Sydney John.
Patel, Framroze Bomanji.
Patel, Shambhubhai Naranbhai.
Payne, Harold Edward.
Pell, Denis Herbert.
Pesikaka, Dosu.
Phillips, George Alfred.
Pilling, Edward.
Plumbly, Geoffrey Morgan.
Ponnaiya, Ambrose George M.
Pook, Cyril Henry.
Prebble, Ronald James.
Priestley, Raymond Edward.
Procter, Frederick Leslie.
Pugsley, Ernest Ronald J.
Pulsford, Henry Eric.
Qurashi, Mohammed Anwar.
Race, Jack Bernard.
Rae, Alan Hugh C.
Rae, Malcolm Harvey.
Rafidi, Farah Isa.
Raj, Cathiresam Pillai M.
Ramakrishnan, G.
Ramakrishnan, N.
Ramalingappa, Nangundappa.
Rama Rao, Kanumilli.
Raman, R. S.
Raman, R. V.
Rane, Kumar Shridhar.
Rao, P. Babu.
Rashid, Mohammad Abdur.
Redding, Robert John.
Reed, John Arthur.
Reed, Neville Stanley.
Reid, James.
Reid, Douglas Justus.

Reza, Azmuth.
Righton, Ronald.
Rikhy, Amolak Singh.
Riley, George.
Rivett, John Colin.
Roberts, John Arthur.
Rochester, John Charles O.
Rogers, John William.
Rogers, Michael Yeates.
Rollo, John Thomas.
Roth, Ronald Charles.
Rothwell, Herbert Kenneth.
Rouse, Herbert James.
Rowe, Douglas Hamilton.
Rowe, Leslie Grimmond.
Rushdi, Rasim.
Russell, Leslie William G.
Sala, Marco Giovanni.
Salt, Eric Douglas S.
Samadani, Ahmad Mukhtar.
Sarma, P. R. Neelakanta.
Schofield, Felix Bowker.
Scholes, Robert Hamer.
Senthinathan, Sivaramalingam.
Sharma, Anand Krishna.
Sharma, Badri Narain.
Sharma, Chandra Lal.
Sharma, Manohar Lal.
Sharrock, Thomas.
Shaw, Alan Linsley.
Shaw, Alexander George.
Shelley, Leslie Hillback.
Shelton, George William.
Sherwood, John Wilson.
Sidhu, Harbhajan Singh.
Simpkins, Robert Arthur.
Sims, Eric Arthur.
Singh, Jogindar.
Sivasamban, Palayavalam Sivaramier.
Smith, Dennis James.
Smith, Harvey Jefferson.
Smith, William Denis A.
Smyth, Stephen Henry.
Snodgrass, William Allan.
Soares, Victor.
Soman, Narayan Shridhar.
Souter, Lesley Scott (Miss).
Speaight, Grahame Horace O.
Spinney, Roger Edwin.
Sreenivasamurthy, B. N.
Stephenson, George William.
Stevenson, Robert Radford.
Soin, Ajab Singh.
South, William Arnold R.
Spencer, Dennis Wilkinson.

Stevens, Norman.
Stewart, Donald.
Stokes, Noel Wood.
Streatfield, Eric Charles.
Subrahmanyam, V. R.
Sud, Mulk Raj.
Sundaram, B.
Suryanarayana, Tata Venkata.
Sutherland, Alexander Thomas.
Swain, John Kenneth.
Tait, Paul John.
Talcherkar, Krishna Vinayak.
Taneja, Rewti Raman.
Tatchell, James Albert.
Taylor, Bernard William.
Taylor, Charles Emery.
Taylor, Ronald Bruce.
Taylor, William Henry.
Terry, Paul Eric A.
Thorpe, Eric.
Tidman, Walter Douglas.
Tiley, Wallace Joseph.
Tote, Balmukund Sayanna.
Tough, James.
Tough, James Leslie.
Treasurer, Vinaykant Dhirajlal.
Trier, Robert Henry.
Twidale, Denis Baron.
Unitt, John Leslie.
Vaidyanathan, Narayanaswamy.
Veerapathiran, Murugason.
Venkatakrishnan, Thiruvenkatanathapuram Ramaswami.
Venn, Mervyn Ernest R.
Vigurs, Reginald Frederick.
Wakeford, Peter Oades.
Walduck, Philip William.
Walker, William Hutton.
Walsh, Maurice Edward.
Walton, William Douglas.
Waters, James Percy.
Watson, Beryl Olive (Miss).
Waugh, George Frederick.
Webb, George Francis H.
Welti, Desmond Gerald.
White, Graham Charles E.
White, William Edward.
Whitehouse, Douglas Charles.
Whitfield, Harold Raymond.
Wickham, George.
Widdowson, John Owen.
Wiffen, Cecil Sidney.
Wiggall, Alfred.

Students—continued.

Wilby, Walter James.
Wild, Henry John.
Wilder, Dion Dealtry.
Wilkins, James Rex.
Williams, Peter.
Williams, Terrence Peter.
Williams, William Arthur W.
Willis, Norman Percy B.
Wilson, Douglas Aird.

Windley, Ronald William.
Winter, Francis Bernard.
Wood, Humphrey.
Woodward, Joseph William.
Wootton, Douglas Jaques.
Wright, John Heward.
Wyke, Richard Edgar B.
Yates, Harold Ashton.

Transfers

Associate Member to Member

Allcock, Harold John, M.Sc.
Baker, John Henry E., B.Sc.(Eng.).
Balbi, Charles Mackenzie R.
Batty, Harry.
Bottomley, William Henry.
Carson, Andrew Howard.
Christie, Thomas Gregg, B.Sc.
Drake, Mervyn George.
Eccles, Josiah, B.Sc.
Egerton, Frank Pownall.
Goodall, John Melville.
Grover, Charles, Major, R.E.
Hall, Roland Charles.
Harle, James Alfred.
Hill, John Noel.
Hill, Wilfred.
Hirst, Allan William, M.Sc. (Eng.).

Hogan, Cecil Frederick.
Holbrook, Henry Stanley, B.Sc.(Eng.).
Jones, John Edwards, B.Sc.
Kennaird, George William.
Mackay, Thomas Whittaker, B.Sc.
McPherson, William Lindsay, B.Sc.
Mundy, Sidney George.
Pidgeon, Joseph Ernest, B.Sc.(Eng.).
Polgreen, Geoffrey Richard, B.Sc.
Ross, William.
Sennett, Harry Hubert.
Sillar, Kenneth Graham.
Stedman, Harold George A.
Wilman, Charles Wilfrid.

Associate to Associate Member

Britton, Charlie Alistair, B.Eng.
Chopra, Hukm Chand, B.Sc.(Eng.).
Clements, Bert Mark.
George, Thomas Alfred.

McGuire, Alexander Thomas.
Murray, John James L., B.Sc.
Richard, Seward Thomas.
Smith, John Johnson.

Wicks, William Edgar.

Graduate to Associate Member

Aldridge, Thomas Jack, B.Sc.
Bassett, Frederick Joseph.
Bate, Rex.
Bates, Harold Thomas.
Batten, Frederick John H.
Bhaumik, Amulya Kumar, B.Sc.(Eng.).
Brabants, Raymond Robert.
Burdick, Robert Harry.
Challis, William Sidney.
Chambers, Arthur Oswald.
Coode, Arthur Michael M.
Delmar-Morgan, Edward Locker.
Dick, Robert Gillon.
Dreyfus, Henry Benfey, B.Sc.Tech.
Fairfield, Ronald McLeod, B.Sc.

Freebody, John William H., B.Sc.(Eng.).
Freeman, Eric Bernard, B.Eng.
Gardner, Harry St. George, B.Sc.
Gibson, John Howell.
Hammersley, Reginald Charles.
Horgan, Michael O'Connor.
Illingworth, Thomas.
Innocent, Harold Frederick.
Jones, Edward Percy H., B.A.
Kearns, Thomas.
Kirkup, Ralph William.
Koh, Nye Poh.
Kouyoumdjian, Vahram T., B.Sc.(Eng.).
Lawrence, Eric Ernest H.
Leek, Thomas William.
Linton, Arthur Hugh F.

Graduate to Associate Member—continued.

Lister, William Clarke, B.Sc.
McKearney, Philip.
Maddison, Walter Hiram, B.Sc.
Maddock, Roger Raymond, B.Eng.
Markland, John Downes.
Merdler, Lionel Reginald.
Moule, John William, B.Sc.(Eng.).
Murray, William James A.
Norfolk, Leslie William, B.Sc.
Oddy, Arthur Herbert S., B.Sc.(Eng.).
Oman, George Rendall, B.Sc.Tech.
Onn, Yeow Tuck, B.Sc.
Paisley, George Albert, B.Sc.(Eng.).
Peacock, James Benzie.
Pearce Donald John, M.Sc.
Philip, William McLaren.
Piper, Ernest Frank.
Procter, Thomas Geoffrey.
Proctor, George Burdett, B.Sc.Tech.
Richardson, Philip.
Rippon, Edward Collingwood.

Roddan, Robert Alexander, B.Sc.
Rose, Victor Reginald.
Sanders, James Curtice.
Sayers, James Edmund, B.Sc.
Schumacher, Charles George.
Sich, Walter Ebray E.
Smith, Leslie Vere.
Stephens, William.
Stevens, Charles Cyril.
Stockings, Thomas.
Sumner, John Houghton, M.Sc.Tech.
Surfleet, Walter Alan.
Sutton, Ernest Joseph.
Taplin, Alfred Eric H., B.Eng.
Underdown, John.
Vivian, William Aubrey, B.Sc.
Waddon, Ernest Avant.
Wallace, George Alister, B.Sc.(Eng.).
West, Francis Richard J.
Whitehouse, Tom.
Williams, Oswald David.
Wilson, James B. E.

Student to Associate Member

Ovens, George, B.Sc.
Paton, Alexander James, B.Sc.

Pritchard, Douglas George.

In addition, the following transfers were effected by the Council at their meeting held on the 6th January, 1938:—

Student to Graduate

Barnard, Arthur Joseph.
Beebe, Ralph David, B.Sc.(Eng.).
Bellairs, Guy ffarington, B.Sc.(Eng.).
Bourne, George Ronald.
Bowyer, Ronald.
Butler, Edward Johnstone, B.Sc.
Child, Arthur Harry.
Crow, Duncan Acheson, B.Sc.(Eng.).
Donald, Lewis Nigel B.
Duncan, Alan Simpson, B.Sc.
Eller, Per Emil R., B.Sc. Tech.
Gill, Maurice, B.Sc.
Gould, William Frederick C.
Gregory, Ronald Hugh.
Haigh, Robert Douglas, M.Eng.
Heppenstall, Frank Evelyn.
Hindle, Thomas, B.Sc.

Hutchinson, Geoffrey Pickworth.
Ireland, John Charles, B.Sc.(Eng.).
Jay, Ronald Arthur.
Keitley, Robert, B Sc.(Eng.).
Knight, Leslie Charles.
Lamb, James.
Law, Harry Bernard, B.Sc.Tech.
Nicholson, William Stanley.
Nisbet, David Ross M.
Paterson, William.
Powley, Reginald Arthur.
Purcell, Geoffrey Stuart, B.Sc.Tech.
Seabrook, Leonard.
Smith, Dennis.
Thomas, Modayil Mani, B.Sc.
Tynan-Byrd, Desmond John.
Watson, John Garth, B.Sc. (Eng.).
Webber, John Clarence.
Wilcox, Leslie Edward, B.Sc.
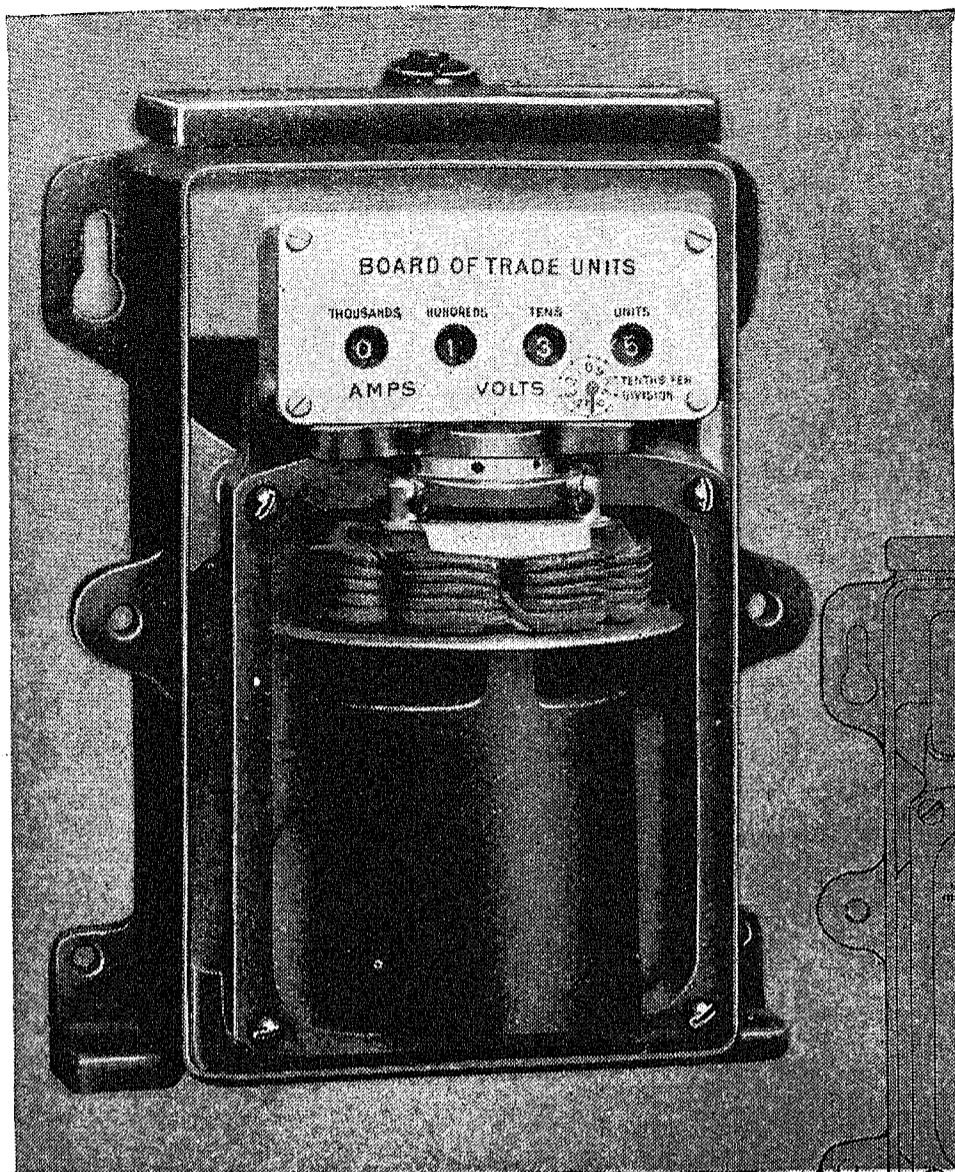
ANNO DOMINI
1903

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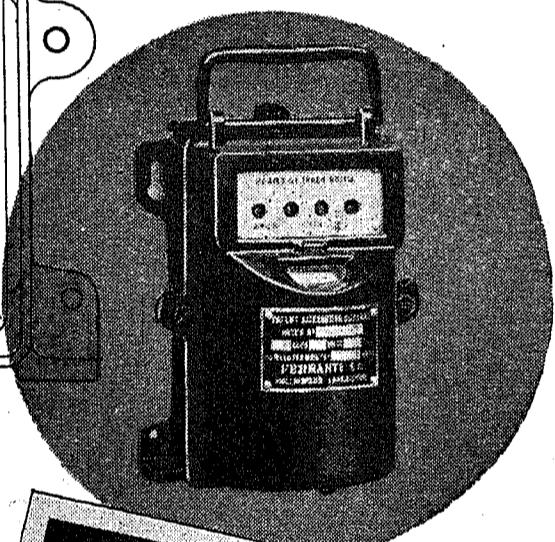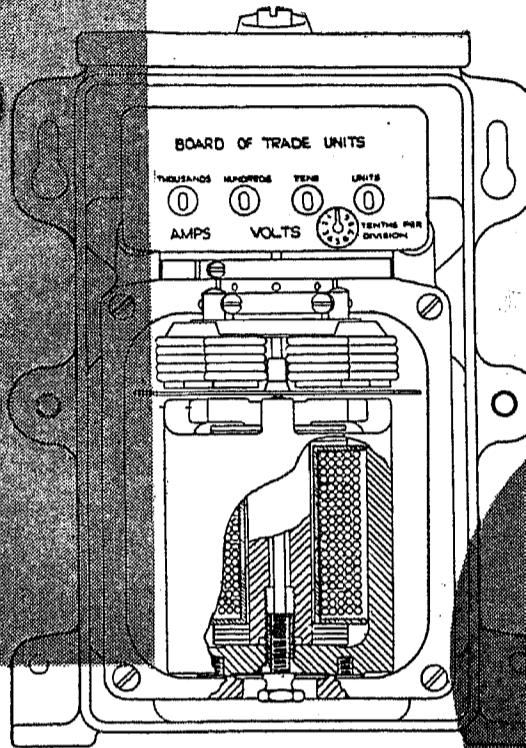
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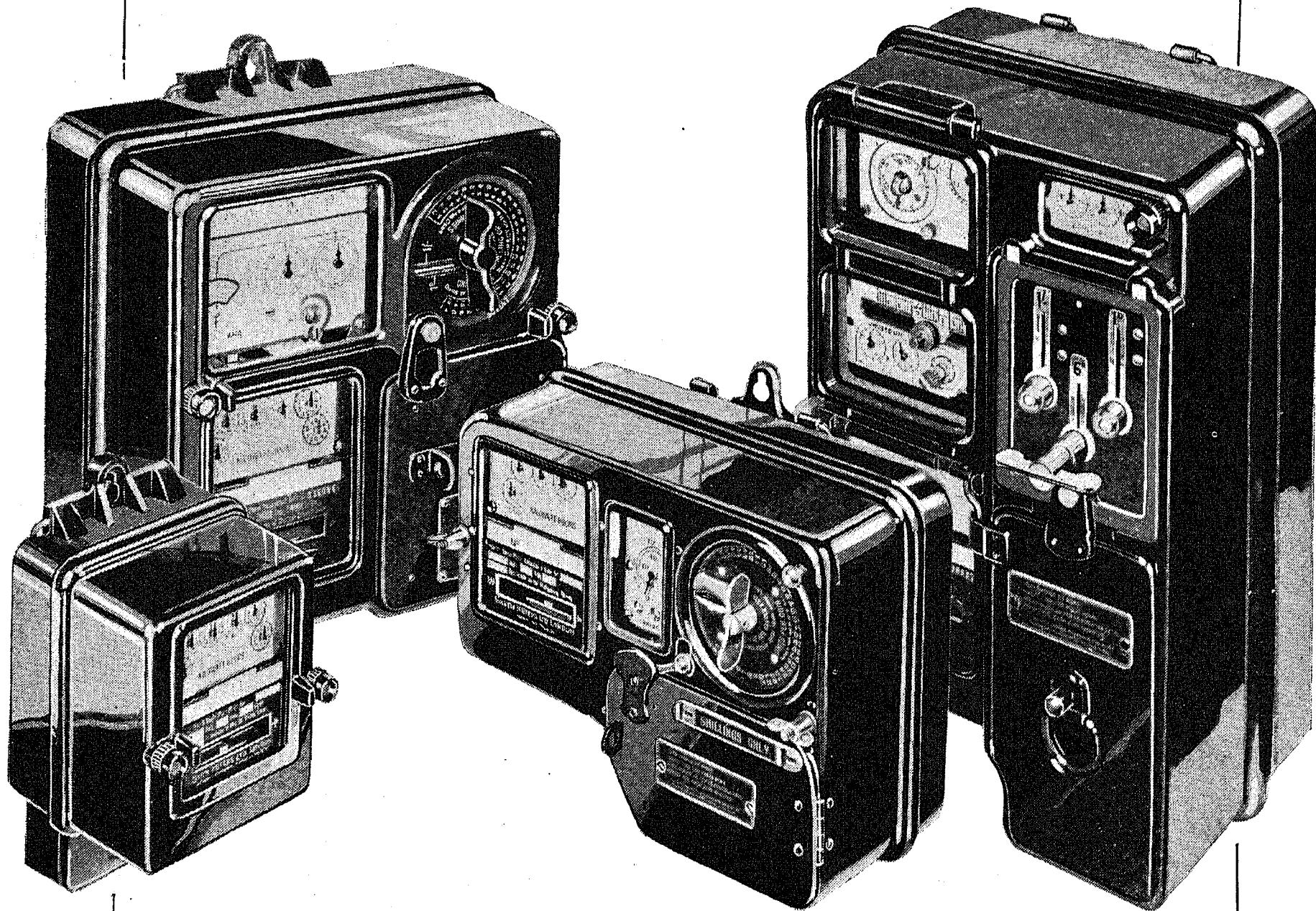
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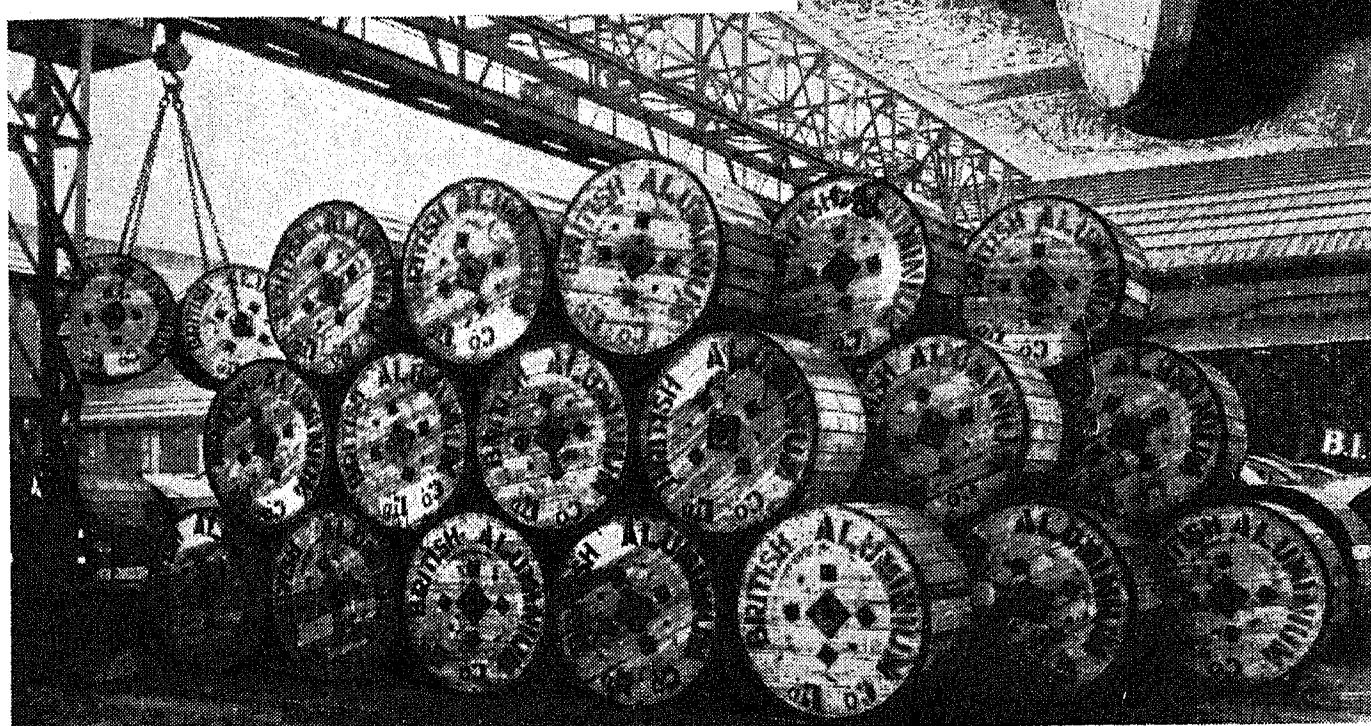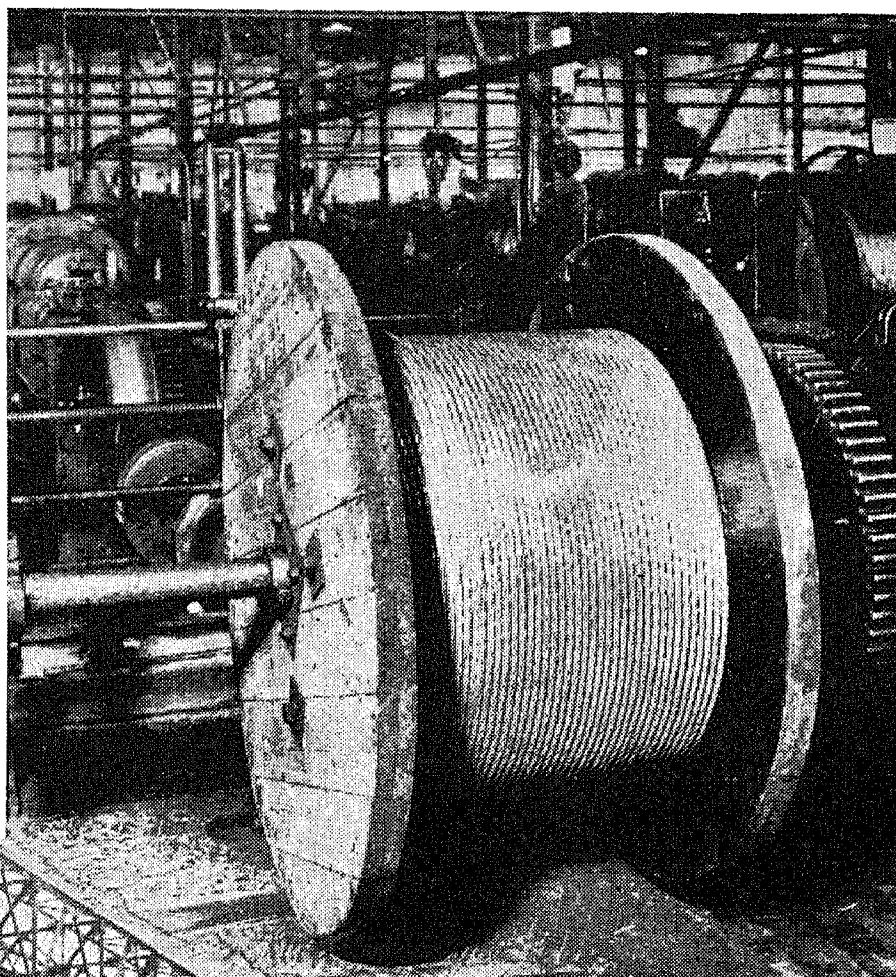
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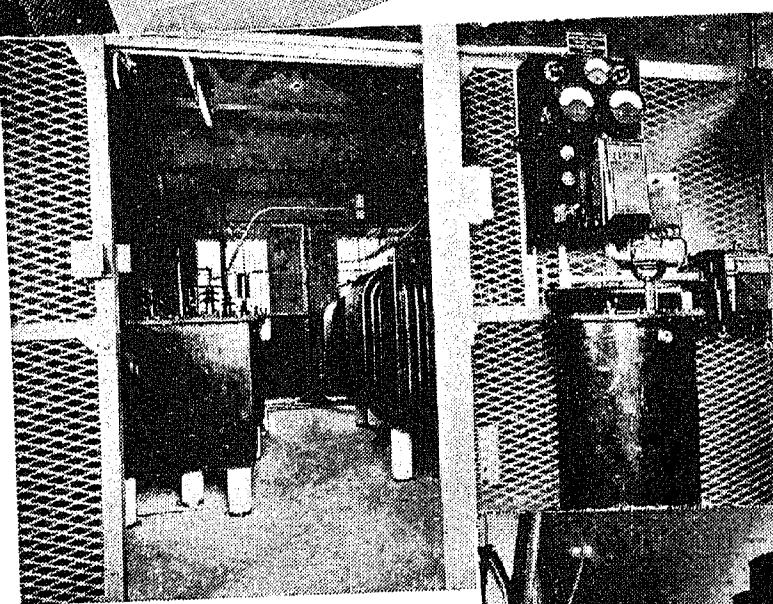
Norwood Coke Works
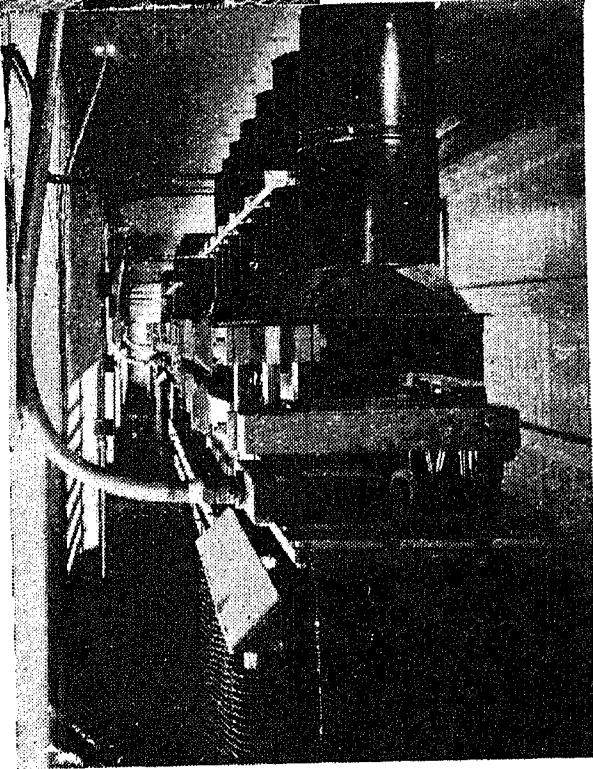
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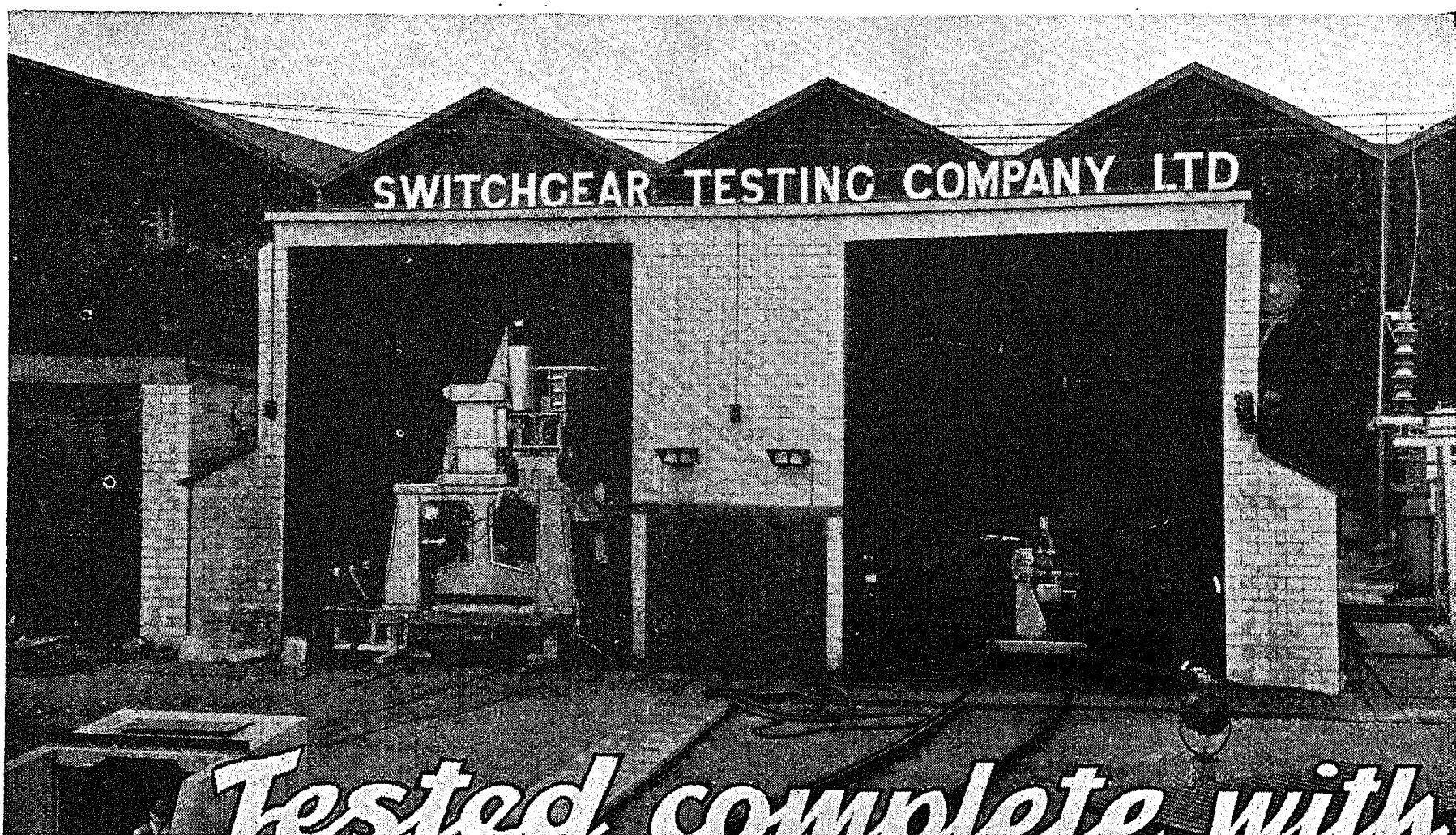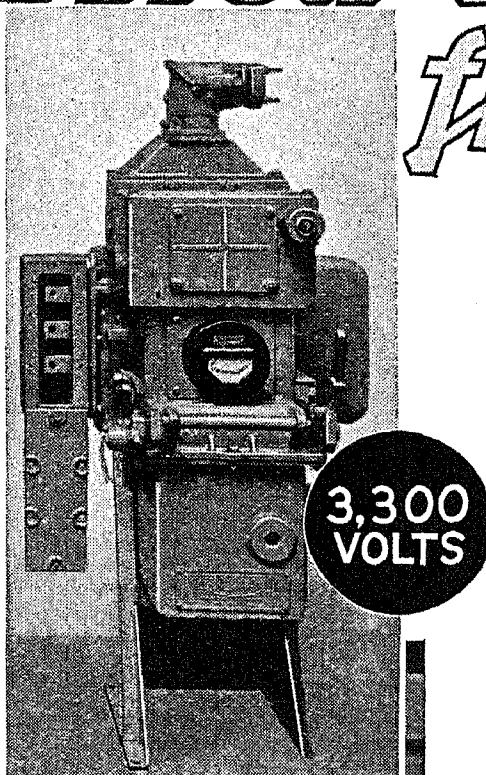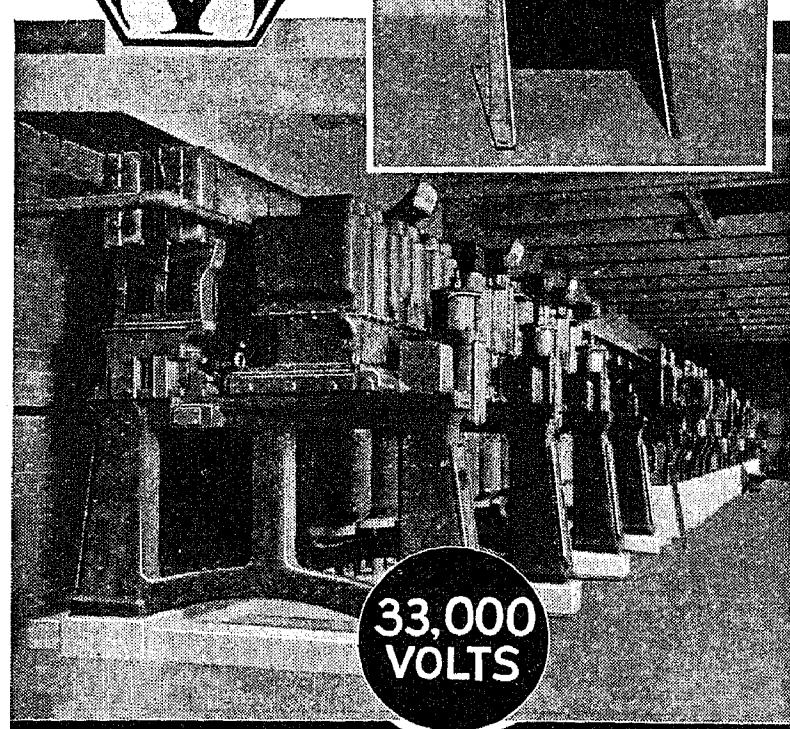
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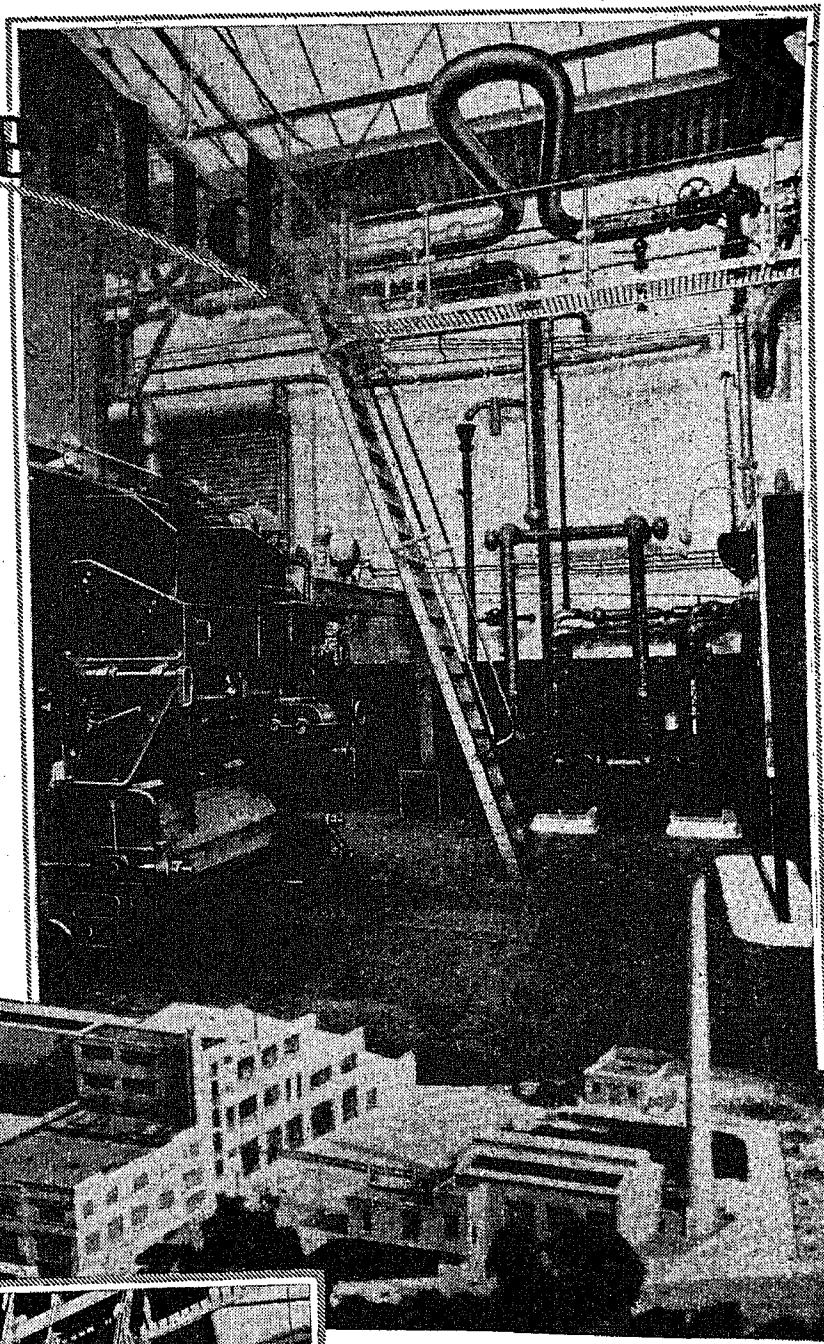
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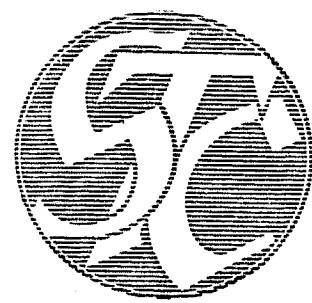
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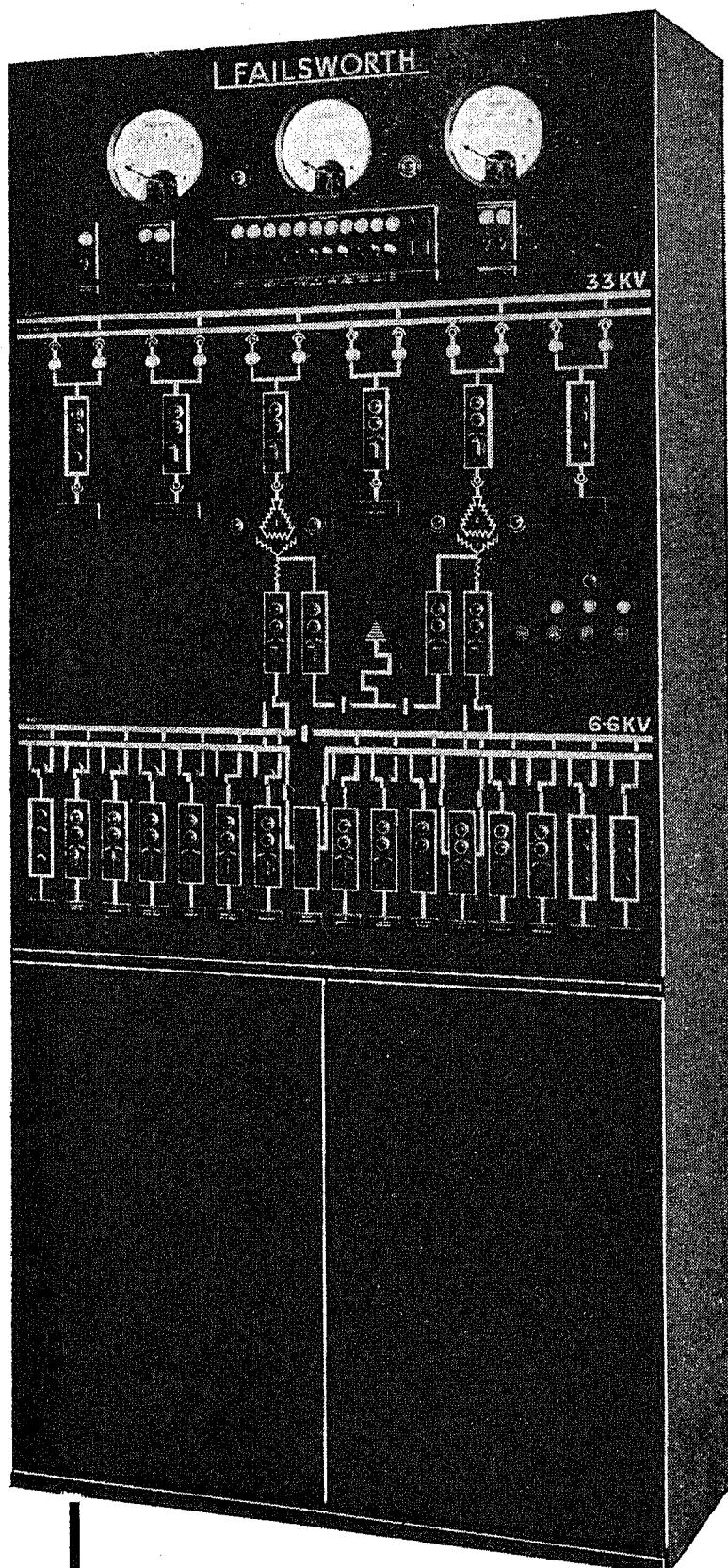
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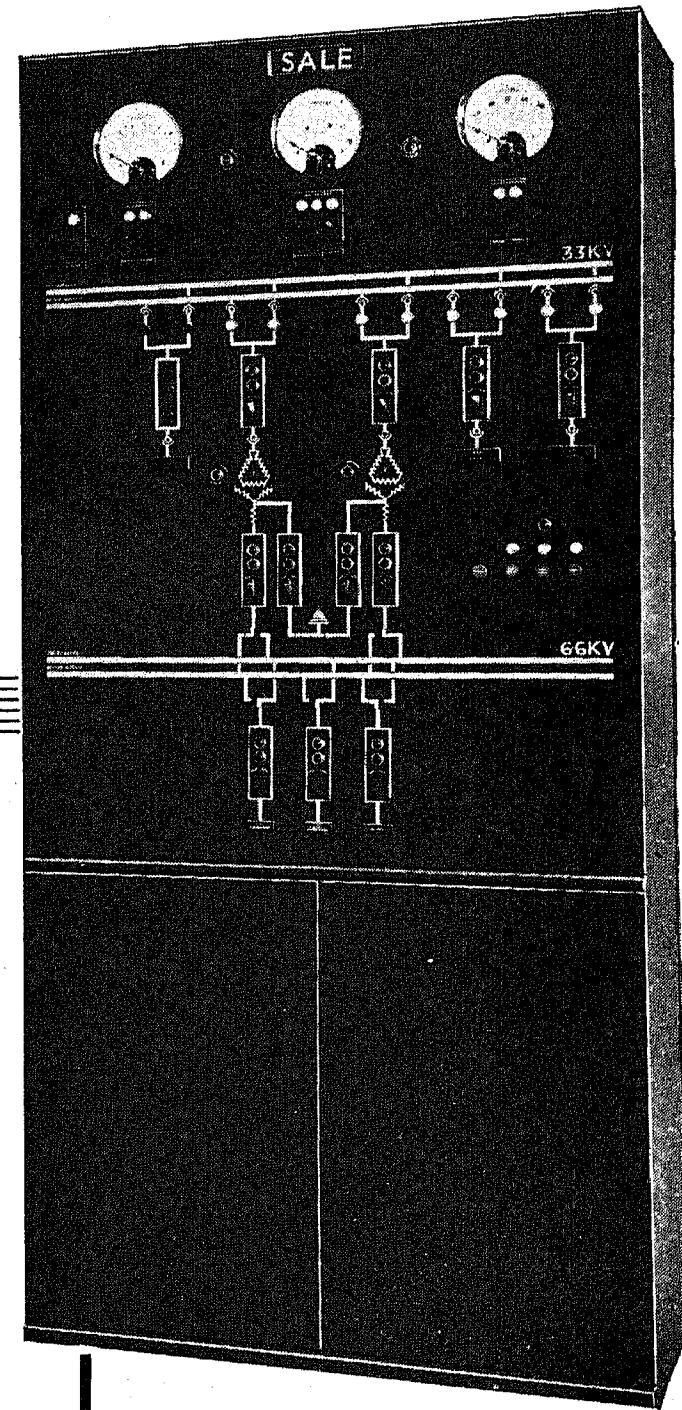
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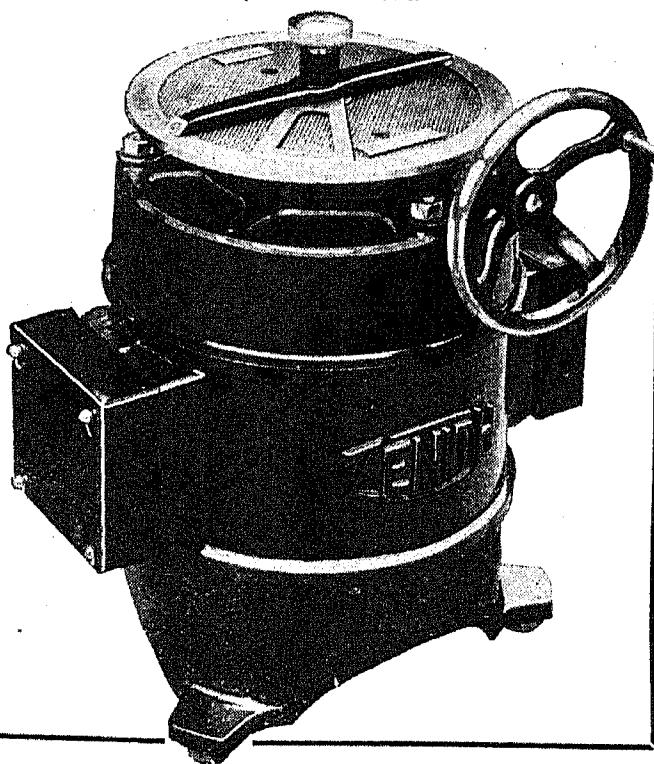
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